GFSSP Training Course

Morning Session

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Thermal & Fluid Analysis Workshop
NASA Johnson Space Center
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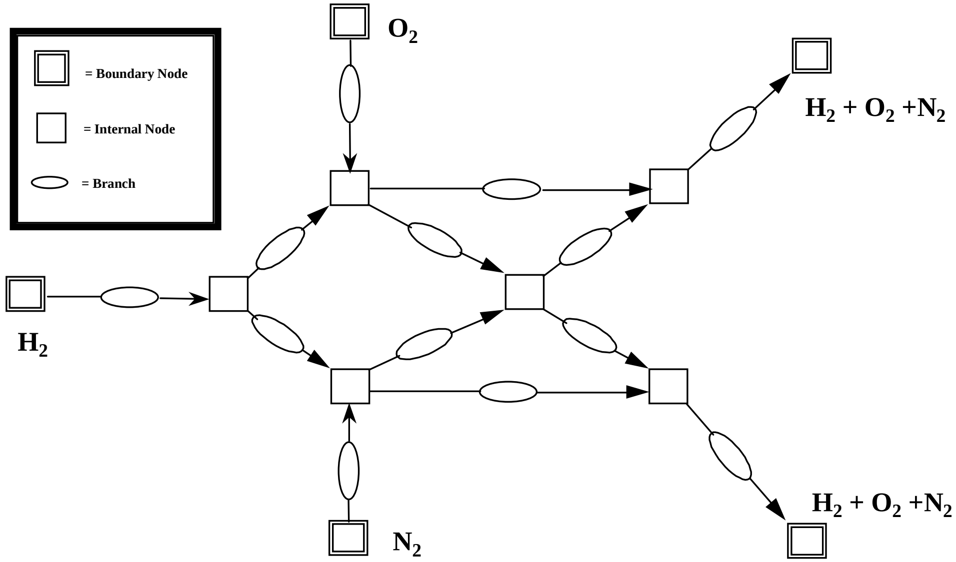
GFSSP - Basic

- Introduction
- Pre & Post Processor – VTASC
- Break
- Resistance & Fluid Option
- Tutorial on Converging-Diverging Nozzle
- Tutorial on Waterhammer

INTRODUCTION & OVERVIEW



CONTENT

- Introduction
  - Background
  - Course Outline
- Overview
  - Network Flow or Navier Stokes Analysis
  - Network Definition
  - Data Structure
  - Mathematical Formulation
  - Program Structure
  - Graphical User Interface
  - Resistance & Fluid Options
  - Advanced Options
  - Applications

BACKGROUND -1

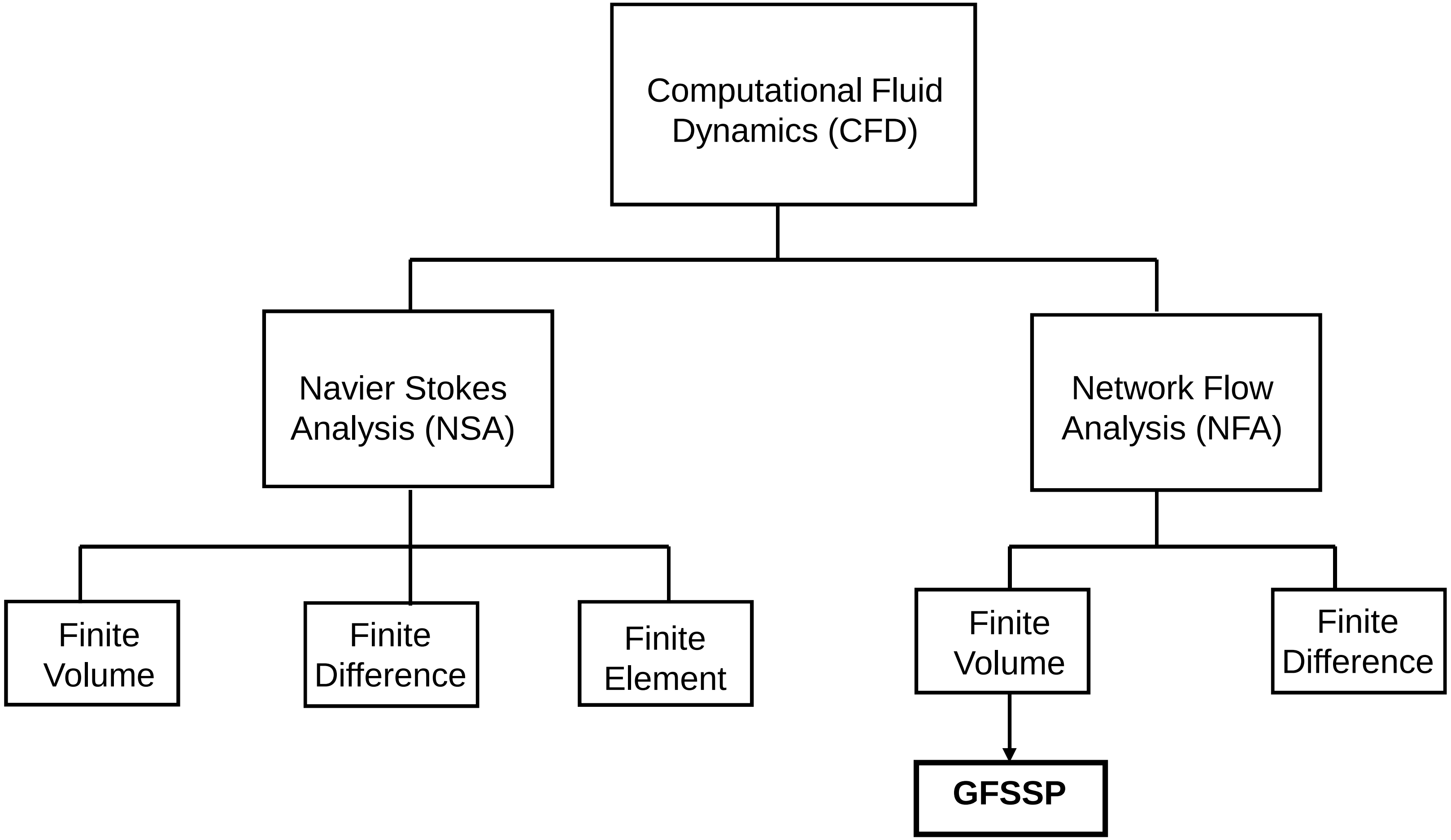
- GFSSP stands for Generalized Fluid System Simulation Program
- It is a general-purpose computer program to compute pressure, temperature and flow distribution in flow network
- It was primarily developed to analyze
  - Internal Flow Analysis of Turbopump
  - Transient Flow Analysis of Propulsion System
- GFSSP development started in 1994 with an objective to provide a generalized and easy to use flow analysis tool

BACKGROUND -2

DEVELOPMENT HISTORY

- Version 1.4 (Steady State) was released in 1996
- Version 2.01 (Thermodynamic Transient) was released in 1998
- Version 3.0 (User Subroutine) was released in 1999
- Graphical User Interface, VTASC was developed in 2000
- Selected for NASA Software of the Year Award in 2001
- Version 4.0 (Fluid Transient and post-processing capability) is released in 2003

NETWORK FLOW OR NAVIER STOKES ANALYSIS - 1



NETWORK FLOW OR NAVIER STOKES ANALYSIS - 2

Navier Stokes Analysis

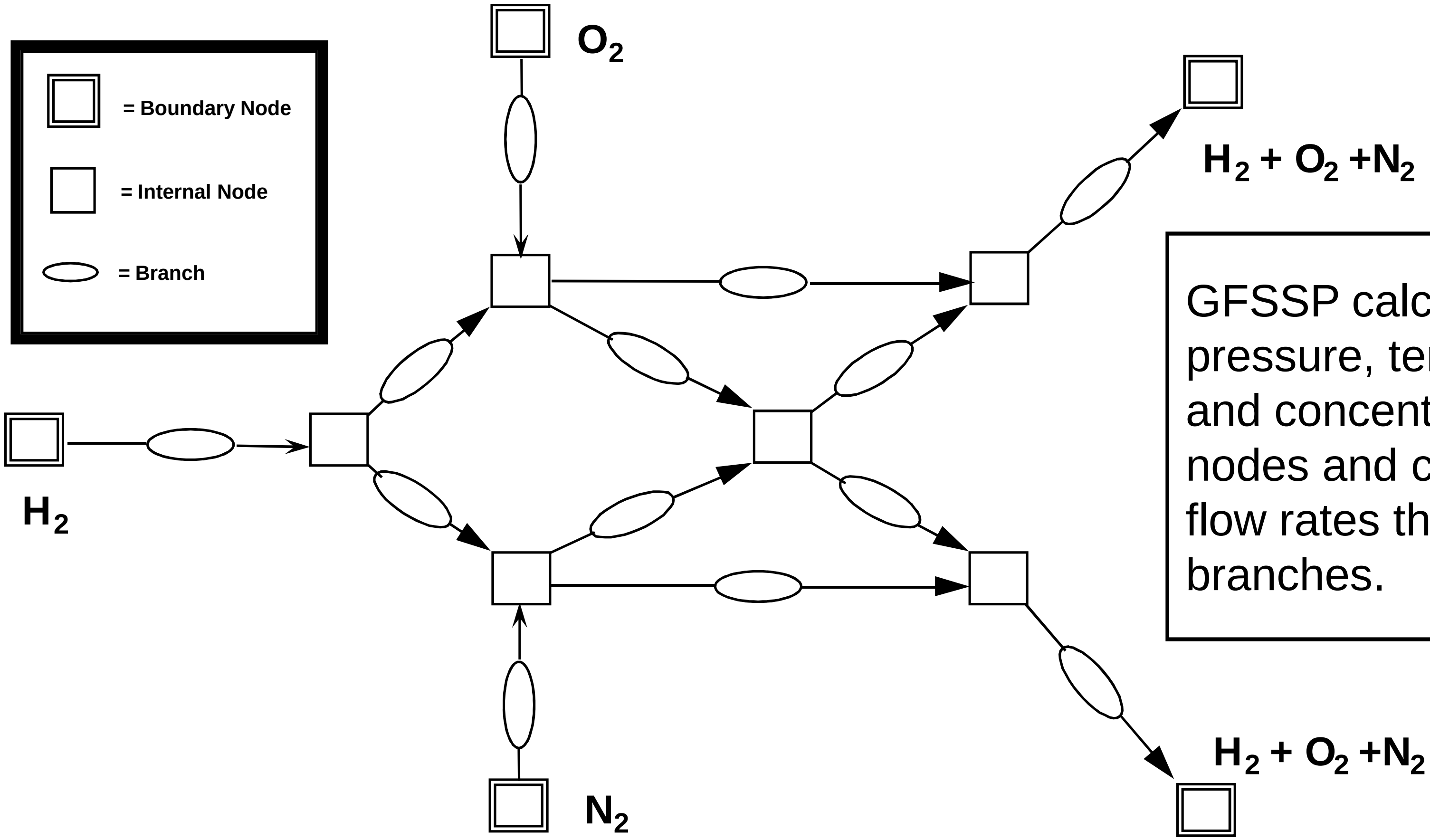
- Suitable for detailed flow analysis within a component
- Requires fine grid resolution to accurately model transport processes
- Used after after preliminary design

Network Flow Analysis

- Suitable for flow analysis of a system consisting of several components
- Uses empirical laws of transport process
- Used during preliminary design

NETWORK DEFINITION – 1

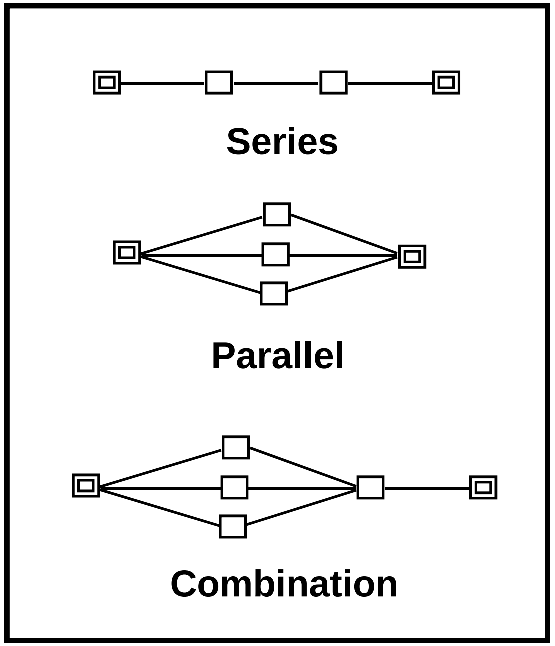
GFSSP FLOW CIRCUIT



GFSSP calculates pressure, temperature, and concentrations at nodes and calculates flow rates through branches.

NETWORK DEFINITIONS - 2

- **Network:**
  - **Boundary node**
  - **Internal node**
  - **Branch**



- **At boundary nodes, all dependent variables must be specified**

- **At internal nodes, all dependent variables must be guessed for steady flow and specified for transient flow.**

NETWORK DEFINITIONS - 3

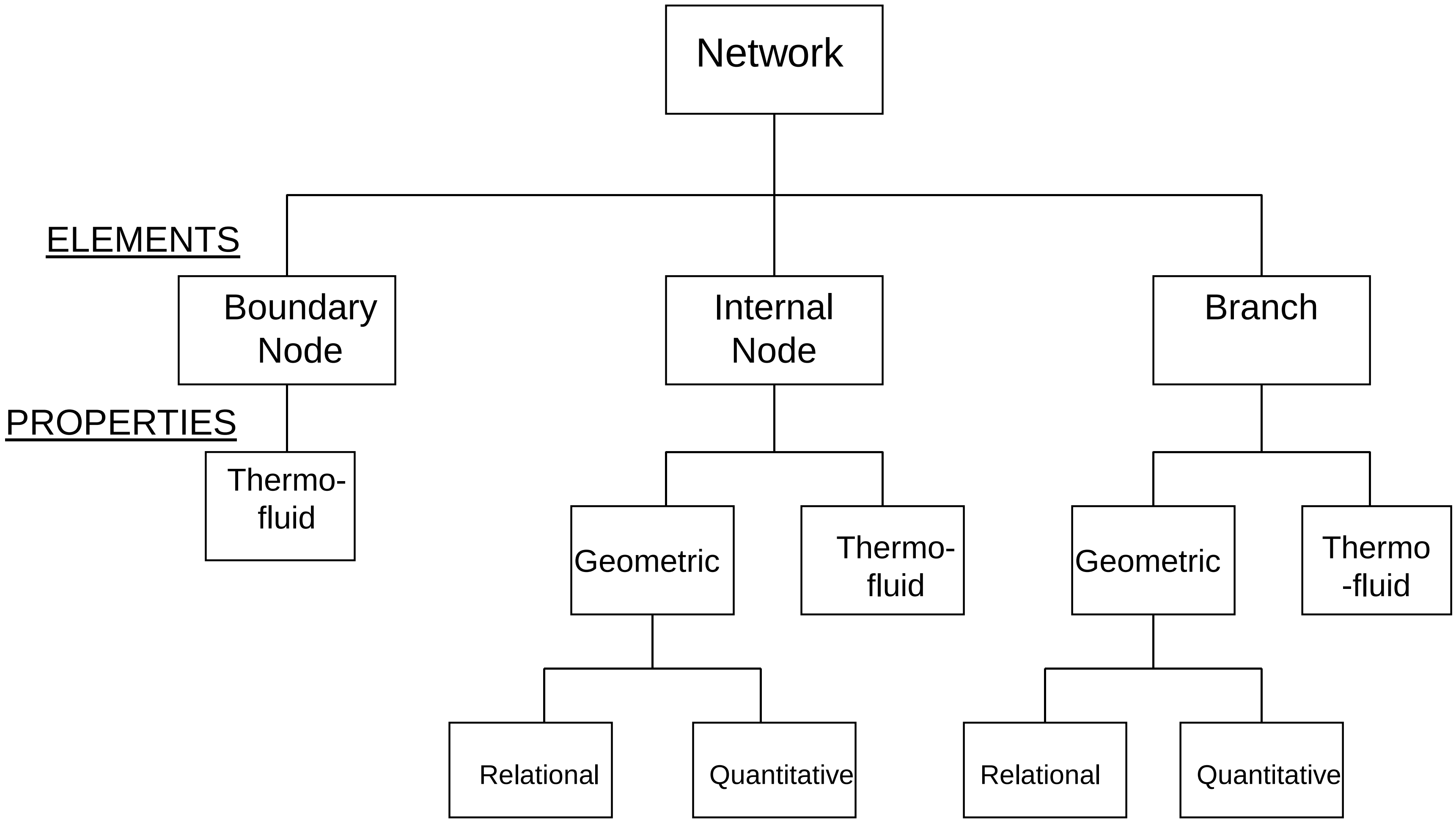
UNITS AND SIGN CONVENTIONS

- Units

	External (input/output)	**Internal** (inside GFSSP)
– Length	- inches	- feet
– Area	- $inches^2$	- $feet^2$
– Pressure	- psia	- psf
– Temperature	- °F	- °R
– Mass injection	- lbm/sec	- lbm/sec
– Heat Source	- Btu/s OR Btu/lbm	- Btu/s OR Btu/lbm

- Sign Convention
  - Mass input to node = positive
  - Mass output from node = negative
  - Heat input to node = positive
  - Heat output from node = negative

DATA STRUCTURE



MATHEMATICAL FORMULATION - 1

MATHEMATICAL CLOSURE - 1

Principal Variables:

Unknown Variables	Available Equations to Solve
1. Pressure	1. Mass Conservation Equation
2. Flowrate	2. Momentum Conservation Equation
3. Temperature	3. Energy Conservation Equation (First or Second Law of Thermodynamics)
4. Specie Concentrations	4. Conservation Equations for Mass Fraction of Species
5. Mass	5. Thermodynamic Equation of State

MATHEMATICAL FORMULATION - 2

MATHEMATICAL CLOSURE -2

Auxiliary Variables:
Thermodynamic Properties & Flow Resistance Factor

Unknown Variables	Available Equations to Solve
Density	
Specific Heats	Equilibrium Thermodynamic Relations
Viscosity	[GASP, WASP & GASPAK Property Programs]
Thermal Conductivity	
Flow Resistance Factor	Empirical Relations

MATHEMATICAL FORMULATION - 3

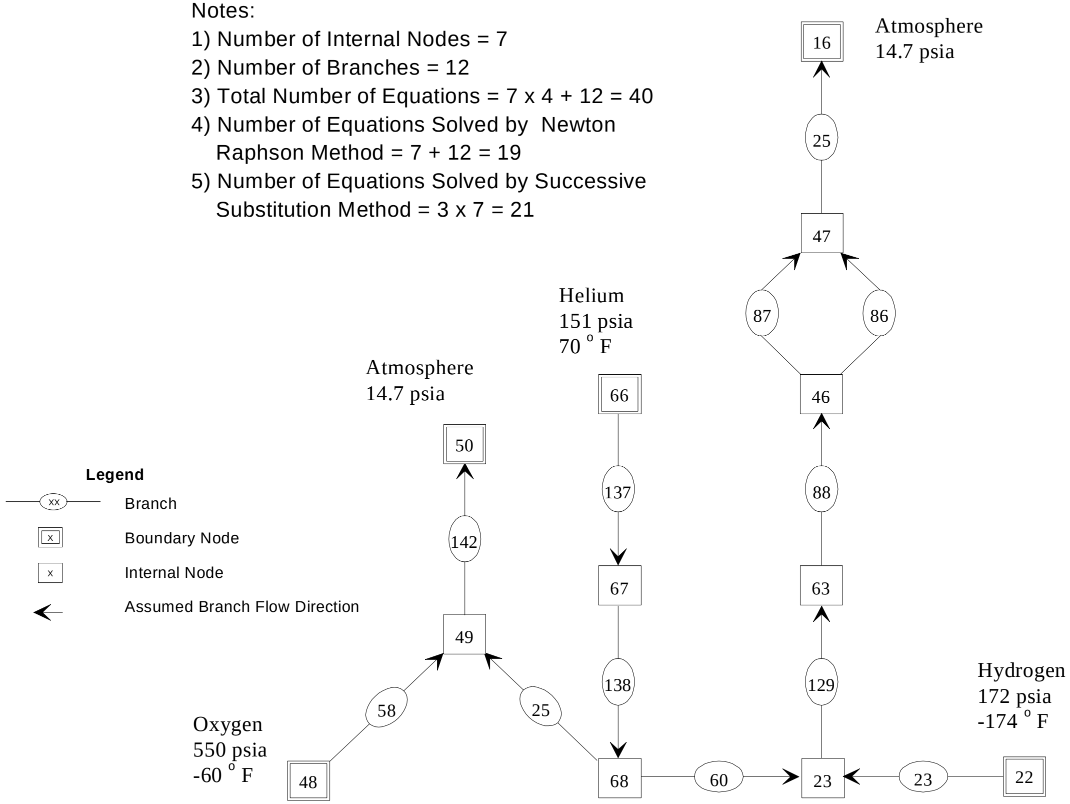
BOUNDARY CONDITIONS

- Governing equations can generate an infinite number of solutions
- A unique solution is obtained with a given set of boundary conditions
- User provides the boundary conditions

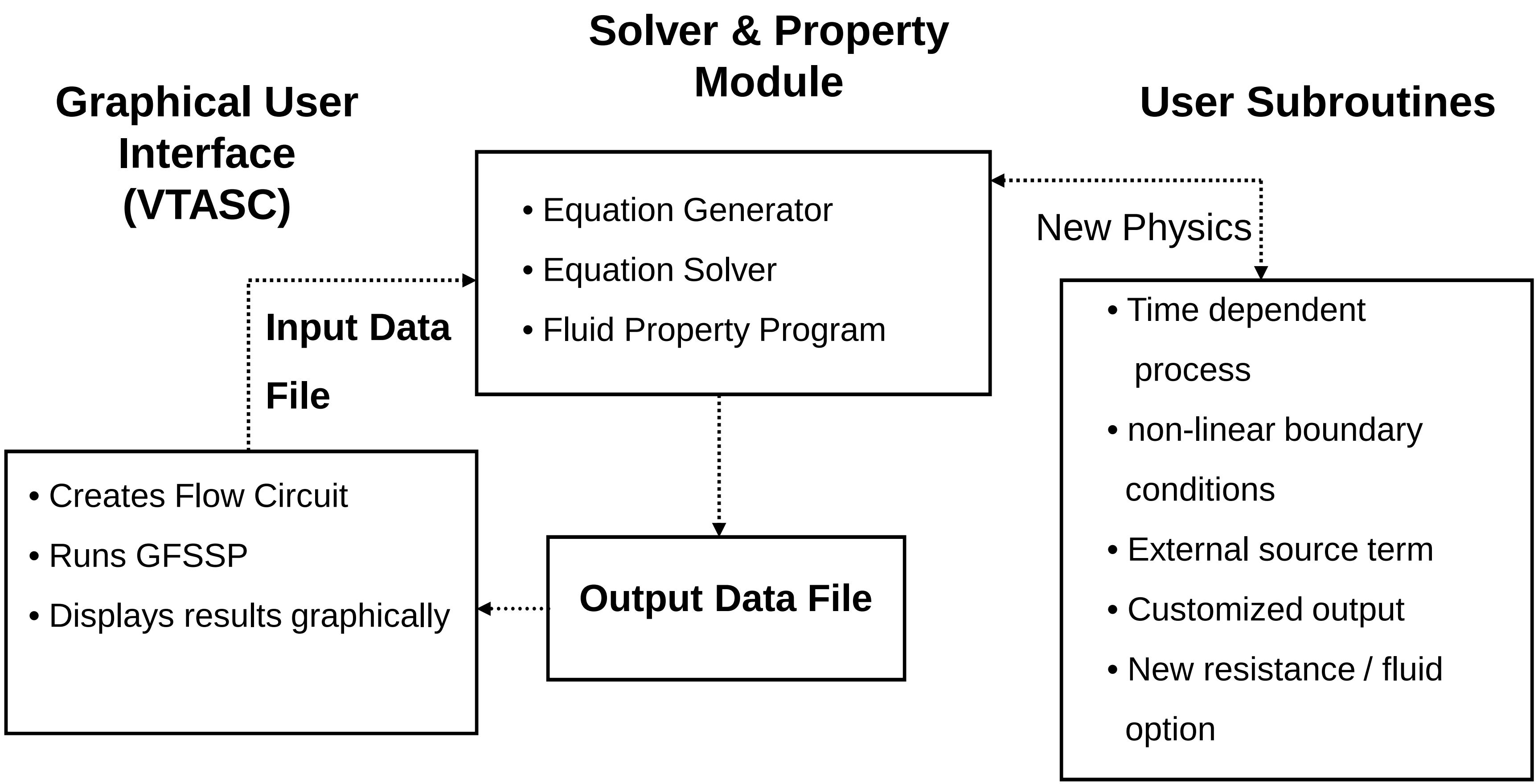
MATHEMATICAL FORMULATION - 3

A TYPICAL FLOW CIRCUIT

Notes:
1) Number of Internal Nodes = 7
2) Number of Branches = 12
3) Total Number of Equations = 7 x 4 + 12 = 40
4) Number of Equations Solved by Newton Raphson Method = 7 + 12 = 19
5) Number of Equations Solved by Successive Substitution Method = 3 x 7 = 21

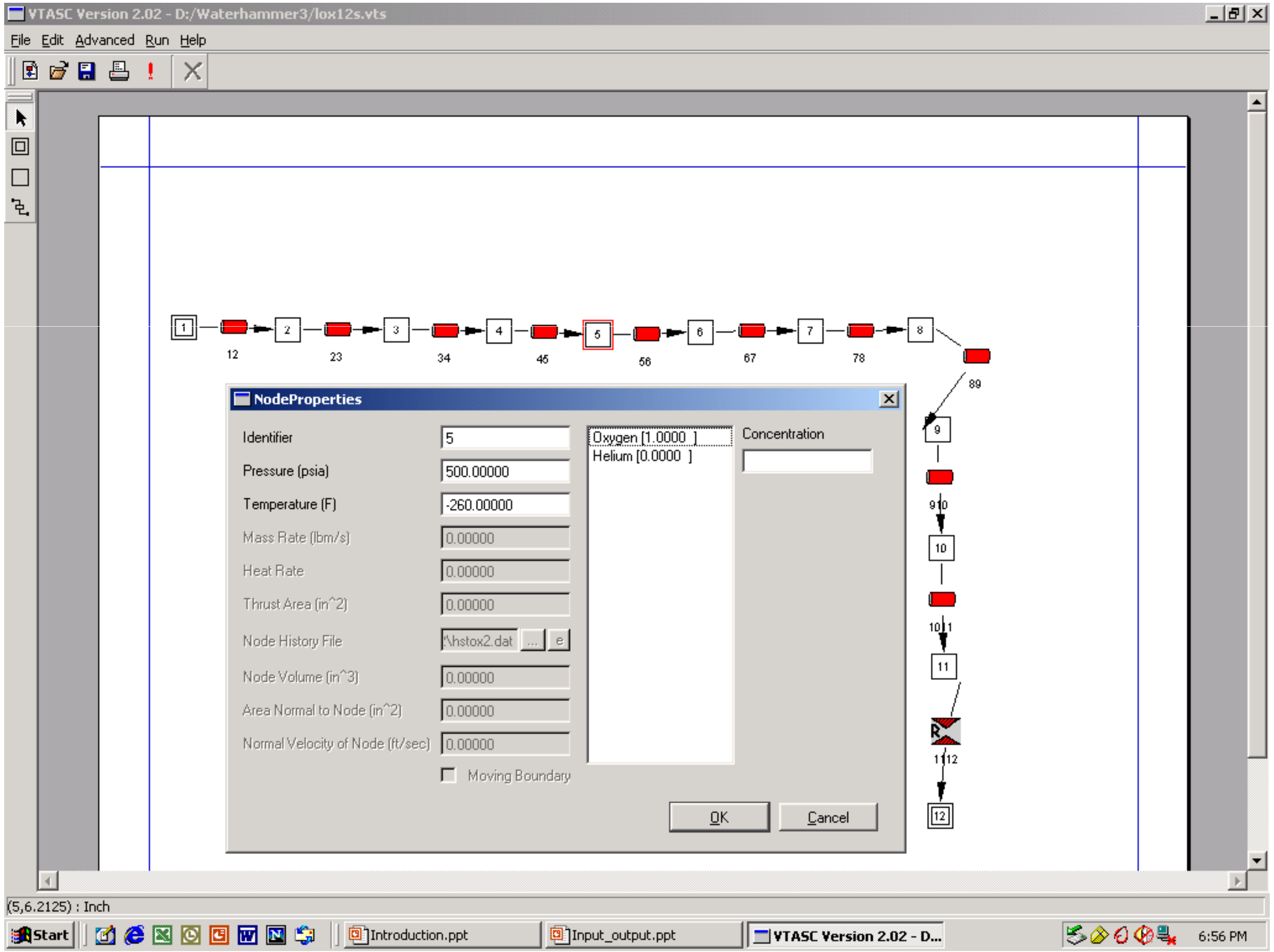


PROGRAM STRUCTURE



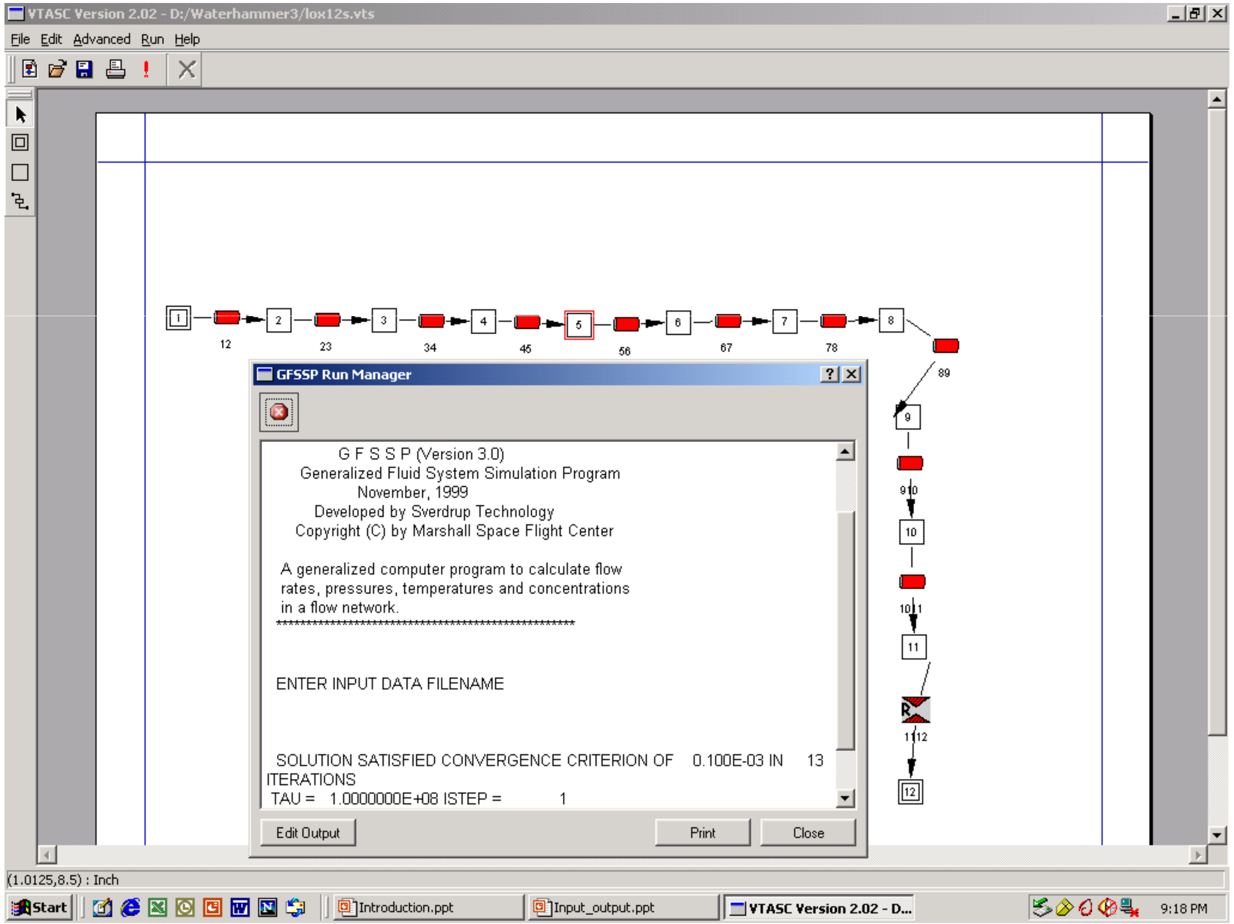
GRAPHICAL USER INTERFACE - 1

MODEL BUILDING



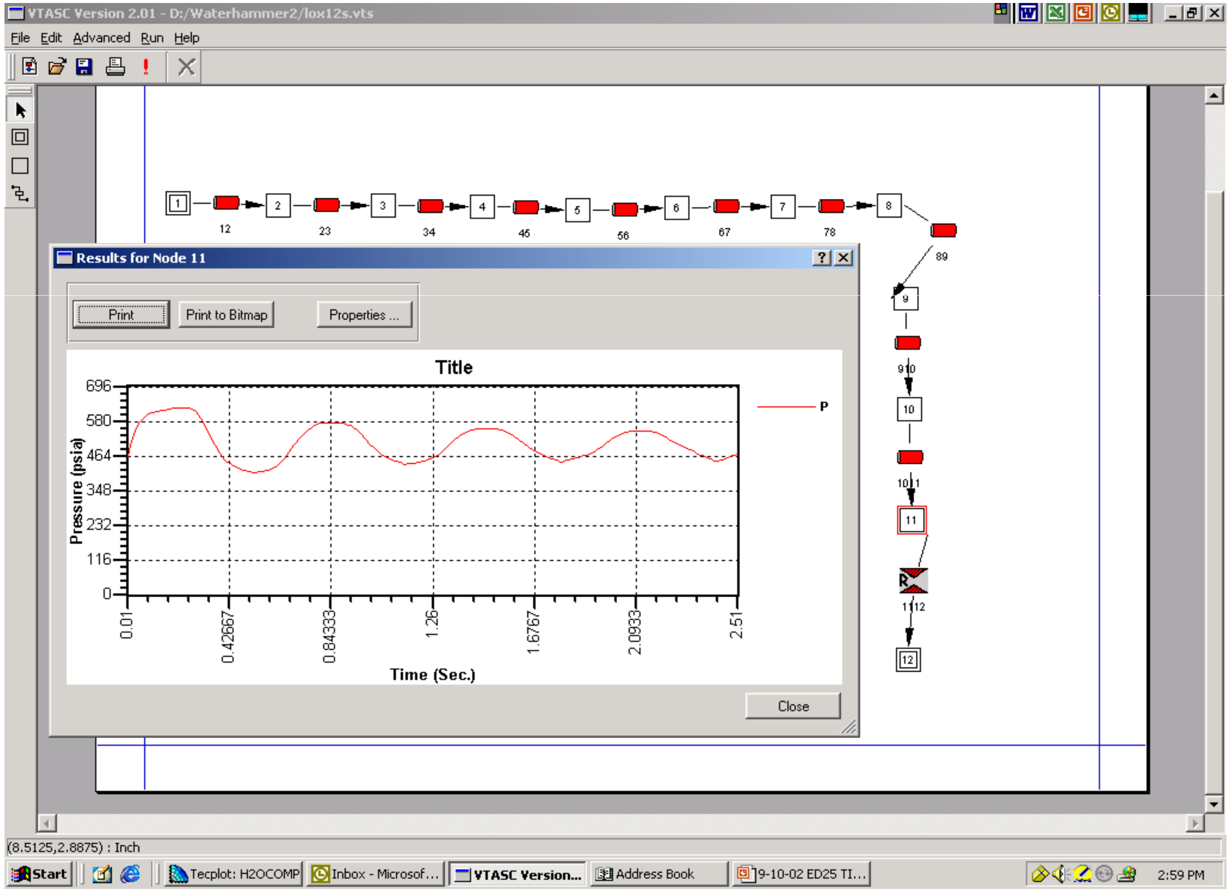
GRAPHICAL USER INTERFACE - 2

MODEL RUNNING

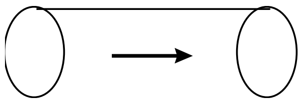


GRAPHICAL USER INTERFACE - 3

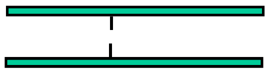
MODEL RESULTS



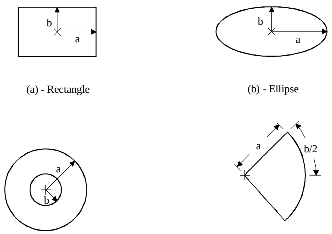
RESISTANCE & FLUID OPTIONS - 1



1. Pipe Flow



2. Flow Through a Restriction



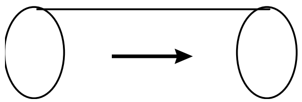
(a) - Rectangle

(b) - Ellipse

(c) - Concentric Annulus

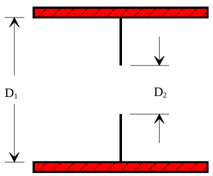
(d) - Circular Sector

3. Non-Circular Duct



4. Pipe Flow with Entrance & Exit Losses

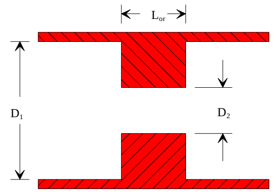
Thin Sharp Orifice



Where:
D_1 = Pipe Diameter
D_2 = Orifice Throat Diameter

5. Thin, Sharp Orifice

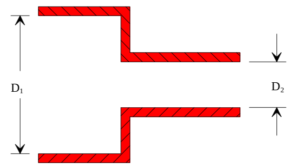
Thick Orifice



Where:
D_1 = Pipe Diameter
D_2 = Orifice Throat Diameter
L_{or} = Orifice Length

6. Thick Orifice

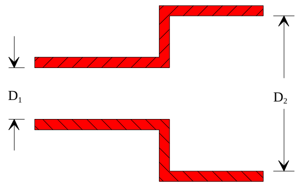
Square Reduction



Where:
D_1 = Upstream Pipe Diameter
D_2 = Downstream Pipe Diameter

7. Square Reduction

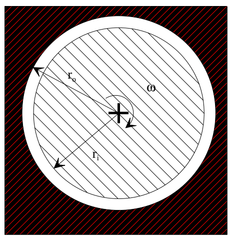
Square Expansion



Where:
D_1 = Upstream Pipe Diameter
D_2 = Downstream Pipe Diameter

8. Square Expansion

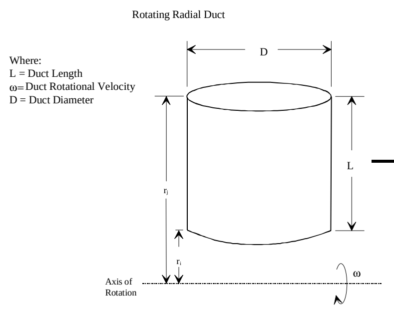
Rotating Annular Duct



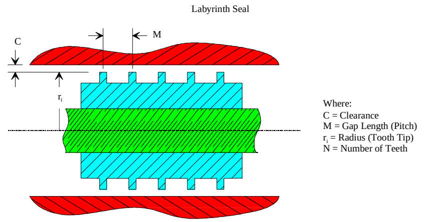
Where:
L = Duct Length (Perpendicular to Page)
b = Duct Wall Thickness ($b = r_o - r_i$)
ω = Duct Rotational Velocity
r_i = Duct Inner Radius
r_o = Duct Outer Radius

9. Rotating Annular Duct

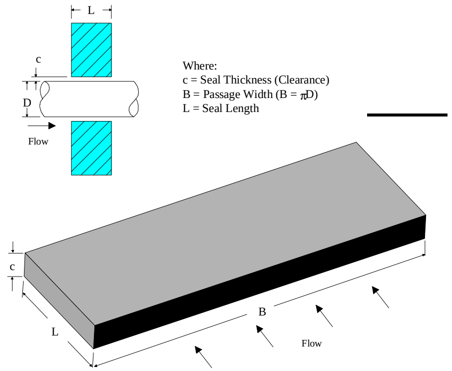
RESISTANCE & FLUID OPTIONS -2



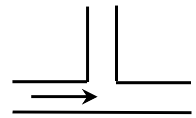
10. Rotating Radial Duct



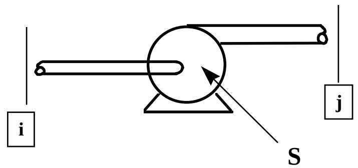
11. Labyrinth Seal



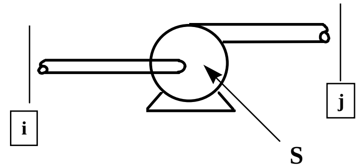
12. Face Seal



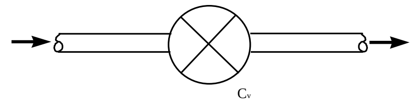
13. Common Fittings & Valves



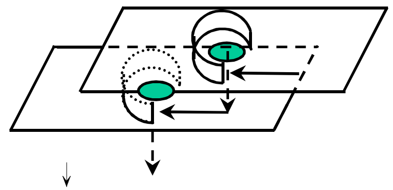
14. Pump Characteristics



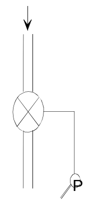
15. Pump Power



16. Valve with Given Cv



17. Viscojet



18. Control Valve

RESISTANCE & FLUID OPTIONS - 3

GASP & WASP

Index	Fluid	Index	Fluid
1	HELIUM	7	ARGON
2	METHANE	8	CARBON DIOXIDE
3	NEON	9	FLUORINE
4	NITROGEN	10	HYDROGEN
5	CARBON MONOXIDE	11	WATER
6	OXYGEN	12	RP-1

RESISTANCE & FLUID OPTIONS - 4

GASPAK

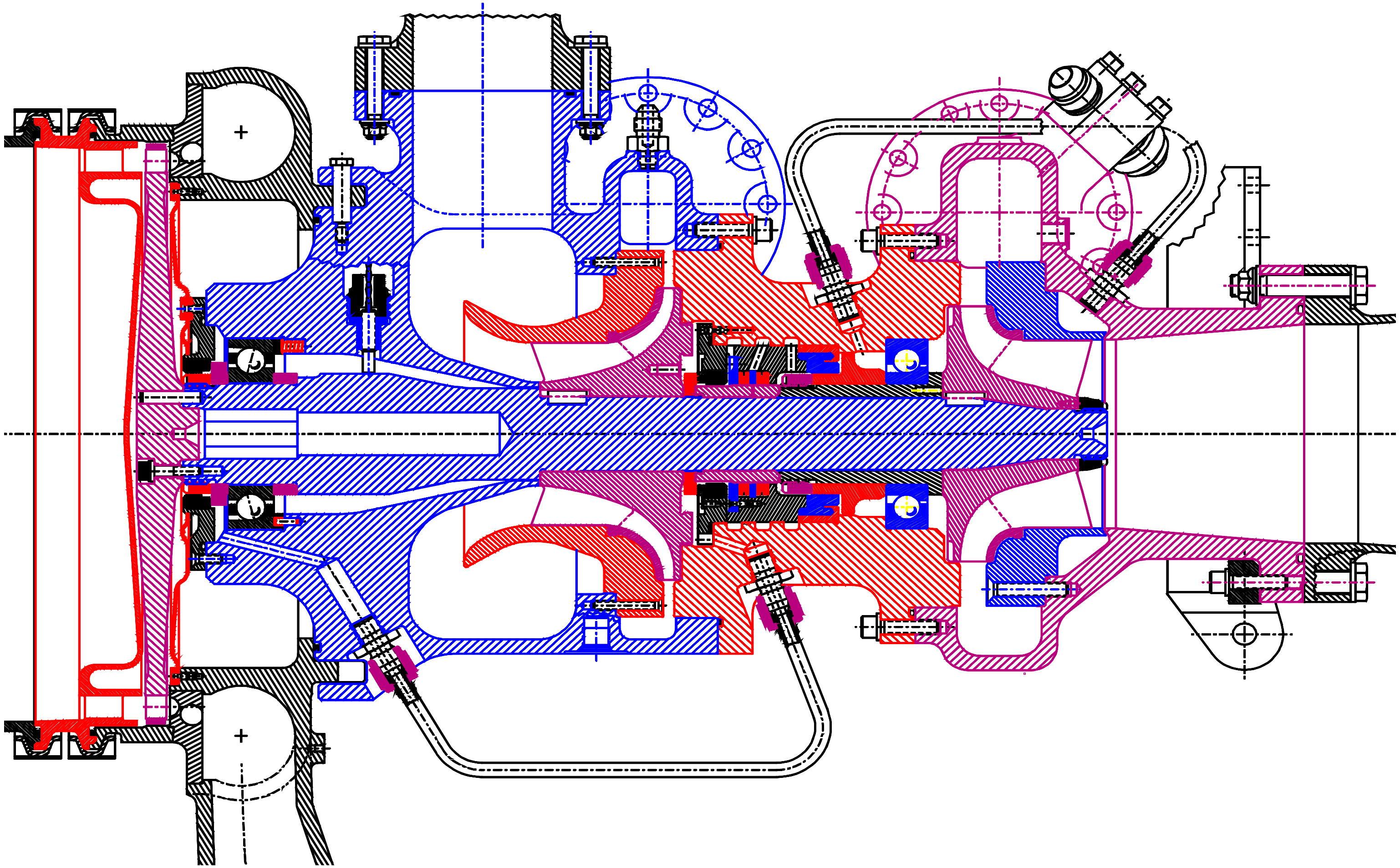
Index	Fluid	Index	Fluid
1	HELIUM	18	HYDROGEN SULFIDE
2	METHANE	19	KRYPTON
3	NEON	20	PROPANE
4	NITROGEN	21	XENON
5	CO	22	R-11
6	OXYGEN	23	R12
7	ARGON	24	R22
8	CO_2	25	R32
9	PARAHYDROGEN	26	R123
10	HYDROGEN	27	R124
11	WATER	28	R125
12	RP-1	29	R134A
13	ISOBUTANE	30	R152A
14	BUTANE	31	NITROGEN TRIFLUORIDE
15	DEUTERIUM	32	AMMONIA
16	ETHANE	33	IDEAL GAS
17	ETHYLENE	34	AIR
		35	HYDROGEN PEROXIDE

ADDITIONAL OPTIONS

- Variable Geometry Option
- Variable Rotation Option
- Variable Heat Addition Option
- Turbopump Option
- Heat Exchanger
- Tank Pressurization
- Control Valve
- Pressure Regulator
- Flow Regulator
- Valve Open/Close (Water Hammer)

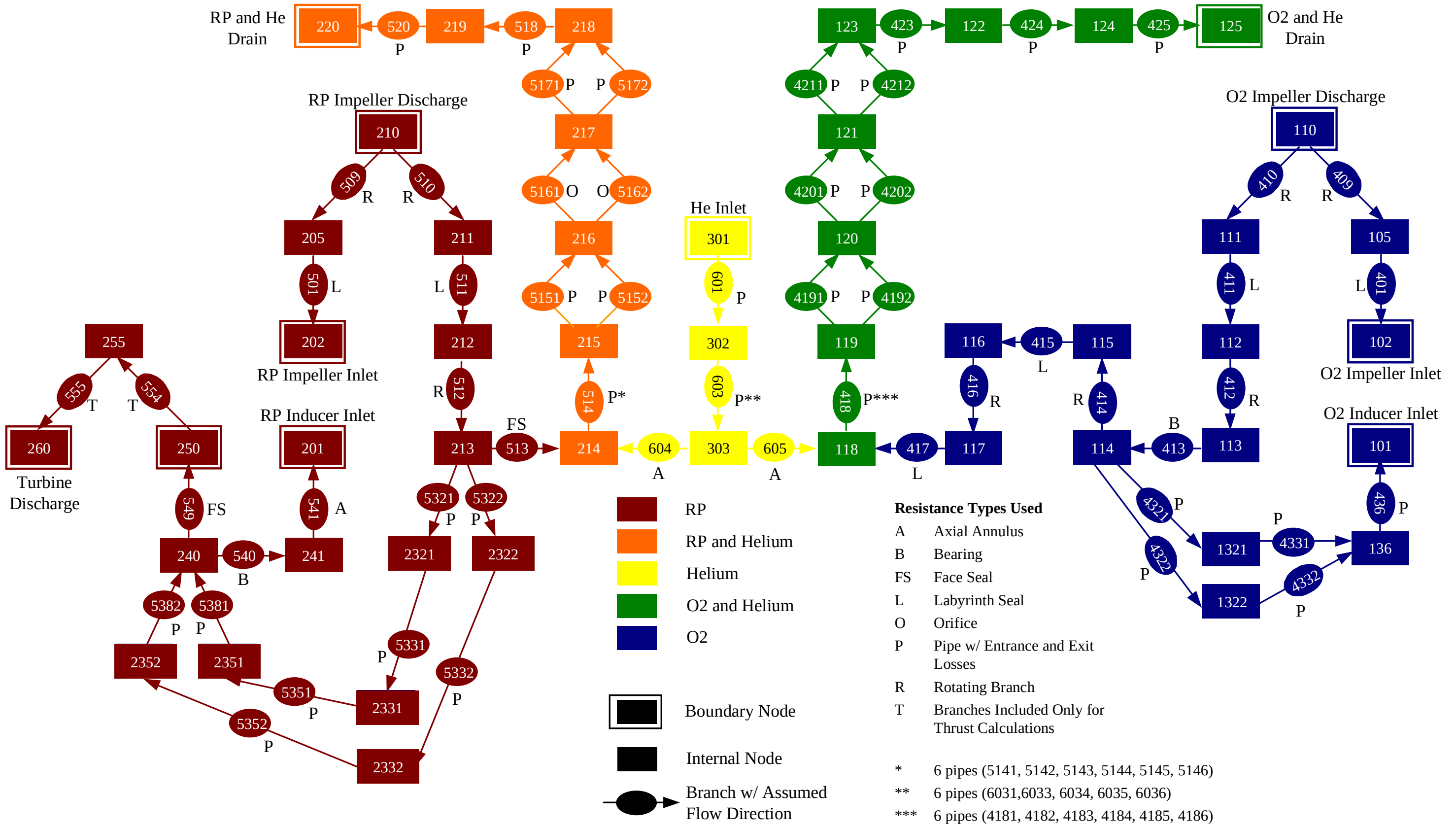
APPLICATIONS - 1

FASTRAC TURBOPUMP



APPLICATIONS - 2

GFSSP Model of the Fastrac Turbopump



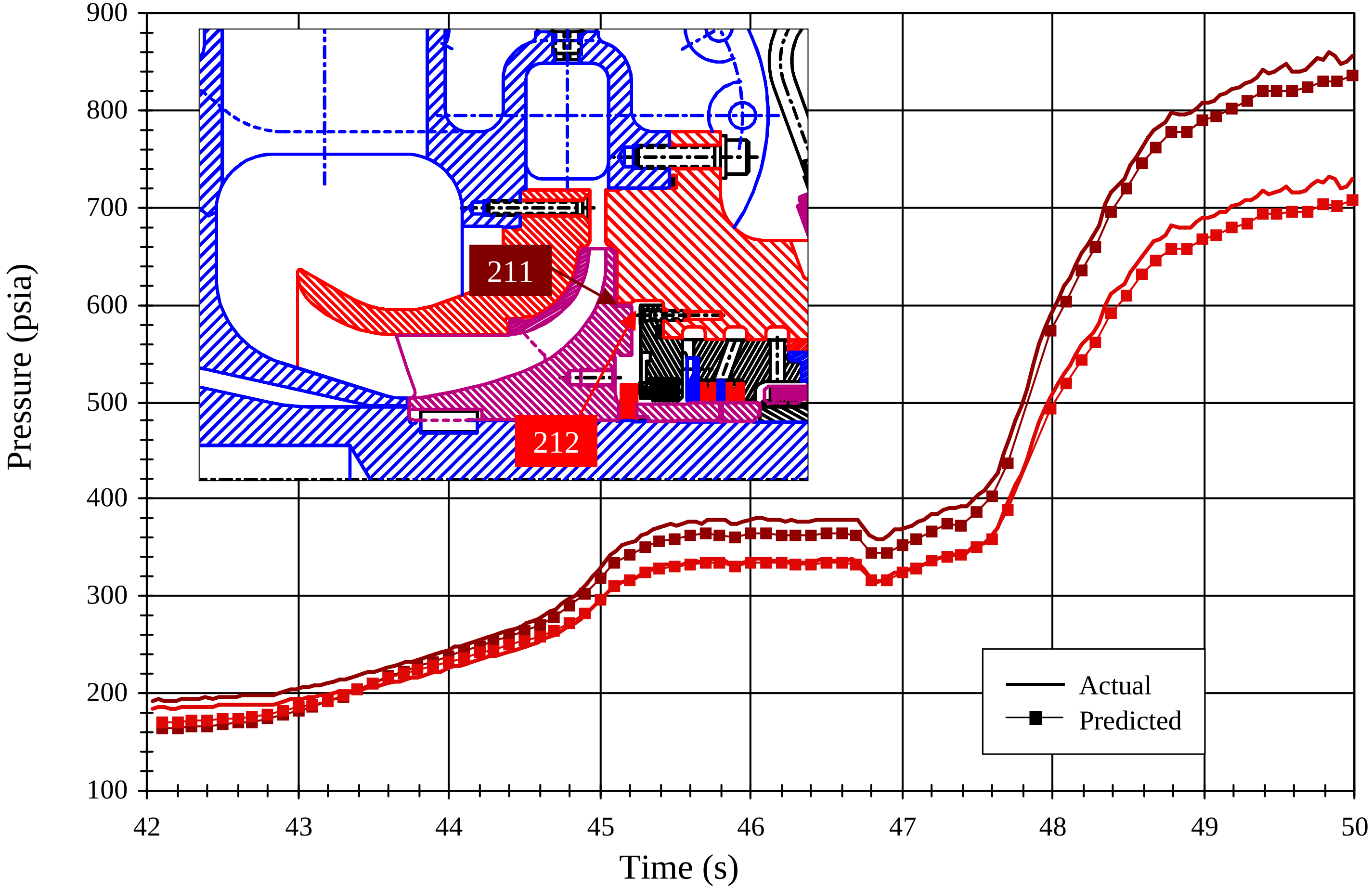
APPLICATIONS - 3

Turbopump Test to 20000 RPM
with Gas Generator

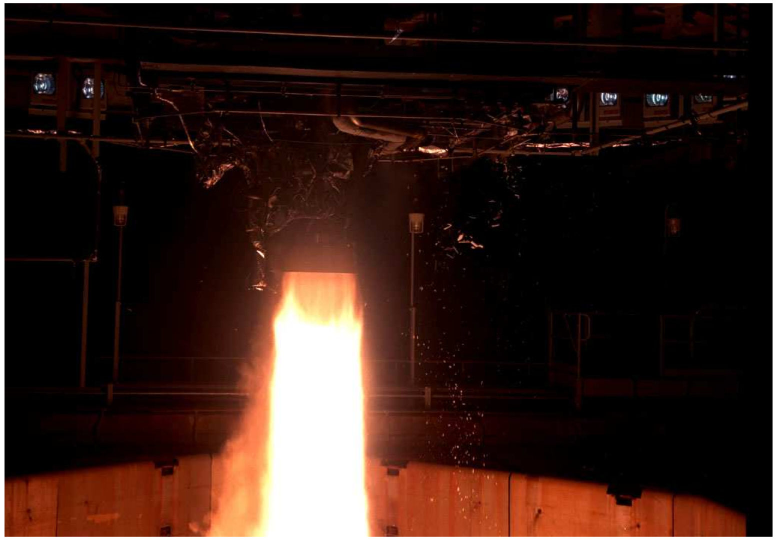
APPLICATIONS - 4

Fastrac Turbopump Model Results

Pressure history comparison at RP-1 Impeller back face [Labyrinth seal inlet (211) and outlet (212)]



APPLICATIONS - 5

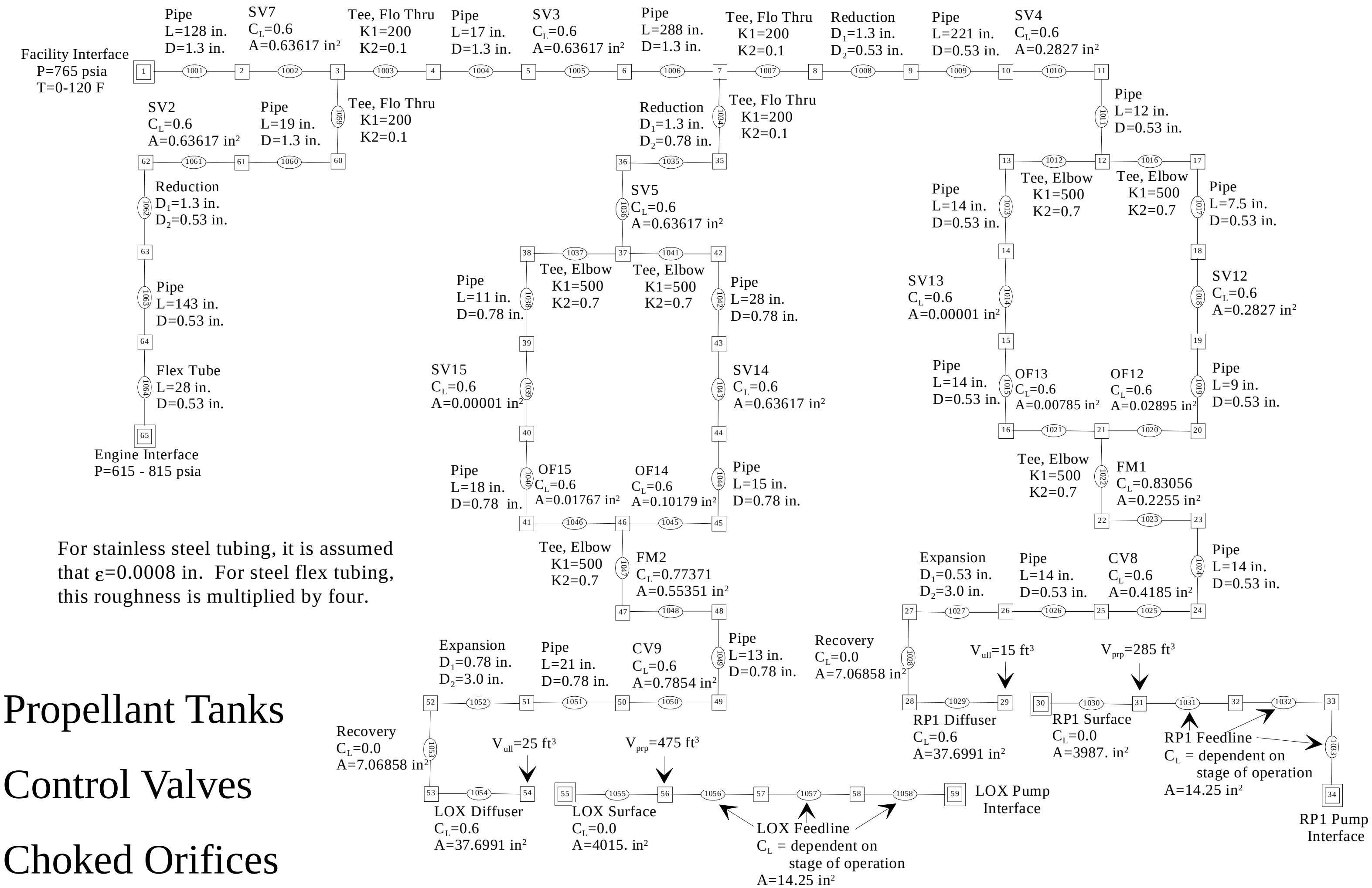


LOX Tank

RP-1 Tank

Engine Interface

GFSSP Model of PTA Helium Pressurization System

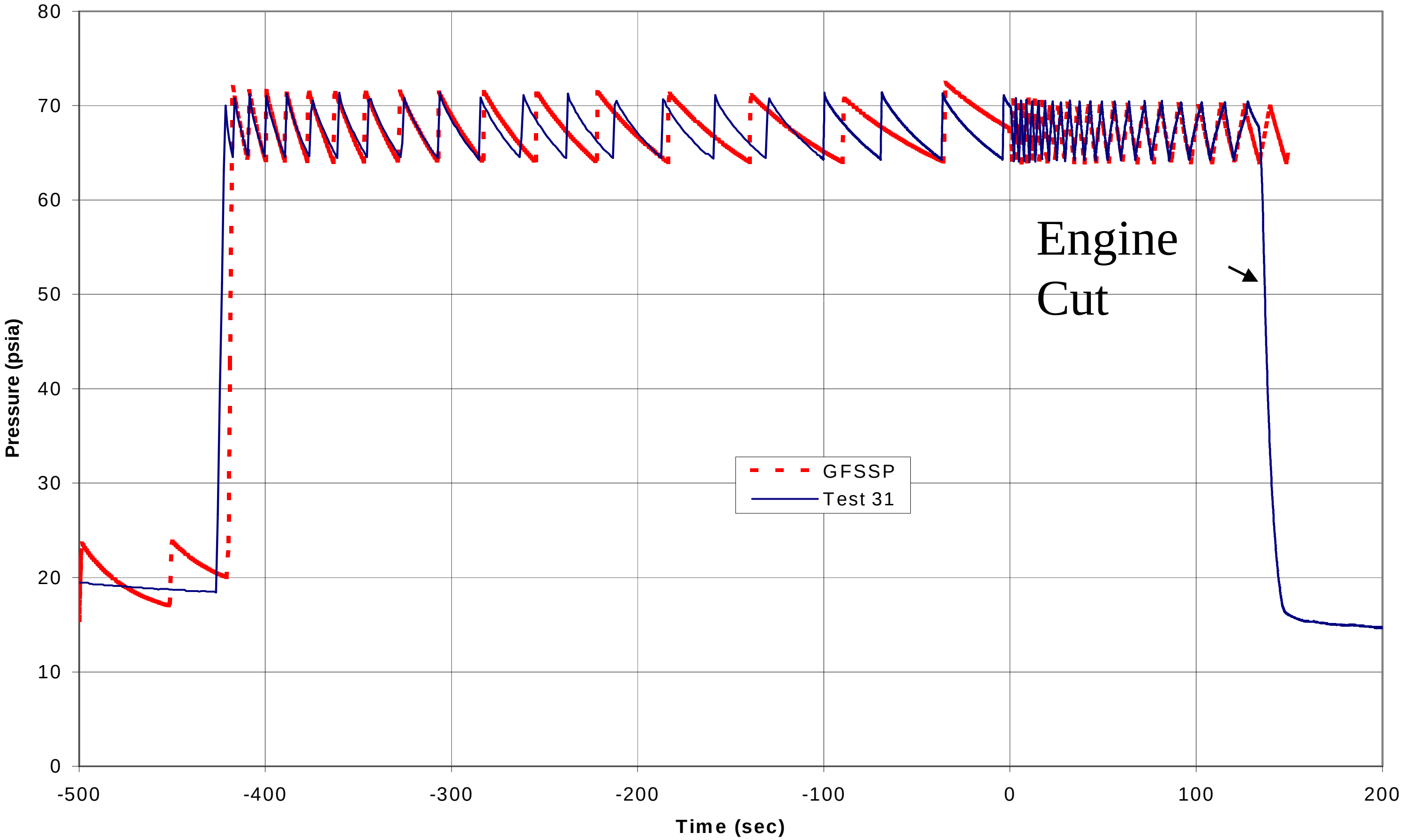


For stainless steel tubing, it is assumed that ε=0.0008 in. For steel flex tubing, this roughness is multiplied by four.

- Propellant Tanks
- Control Valves
- Choked Orifices
- Various fittings

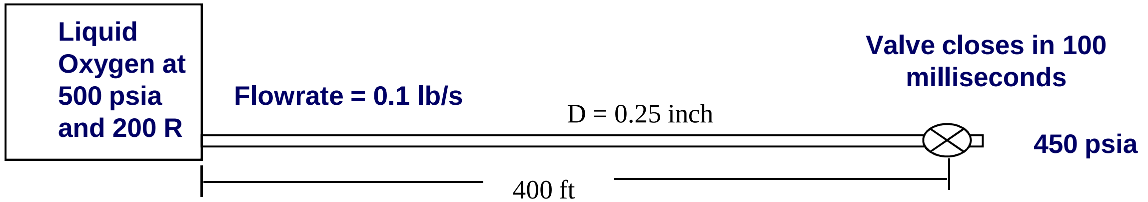
APPLICATIONS - 7

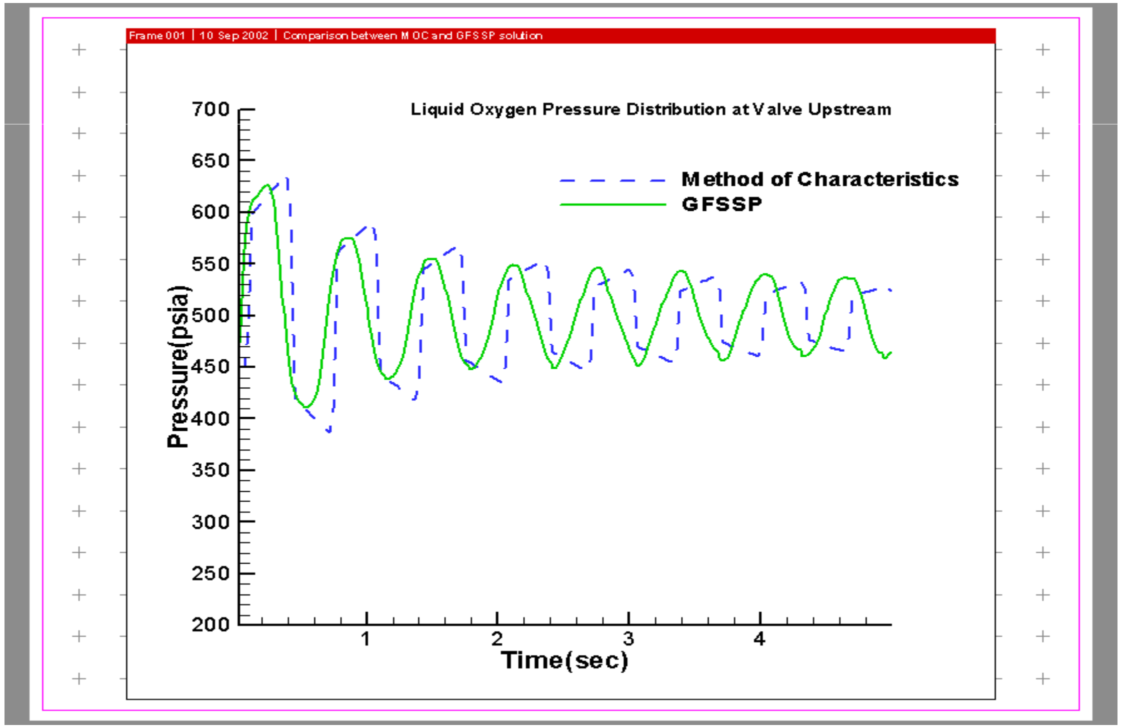
Comparison of LOX Ullage Pressure with Test Data



APPLICATIONS - 8

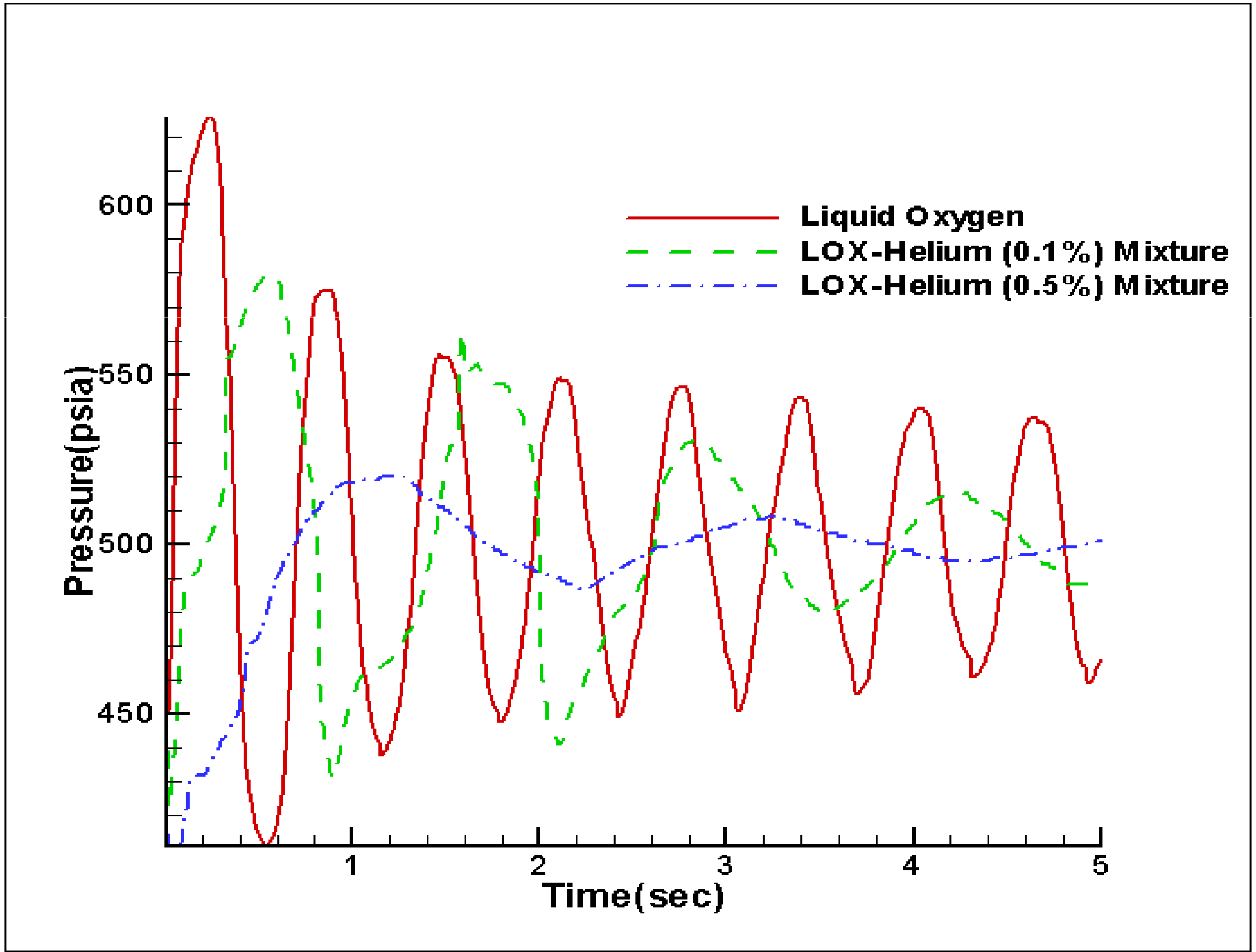
Verification of Fluid Transient Computation





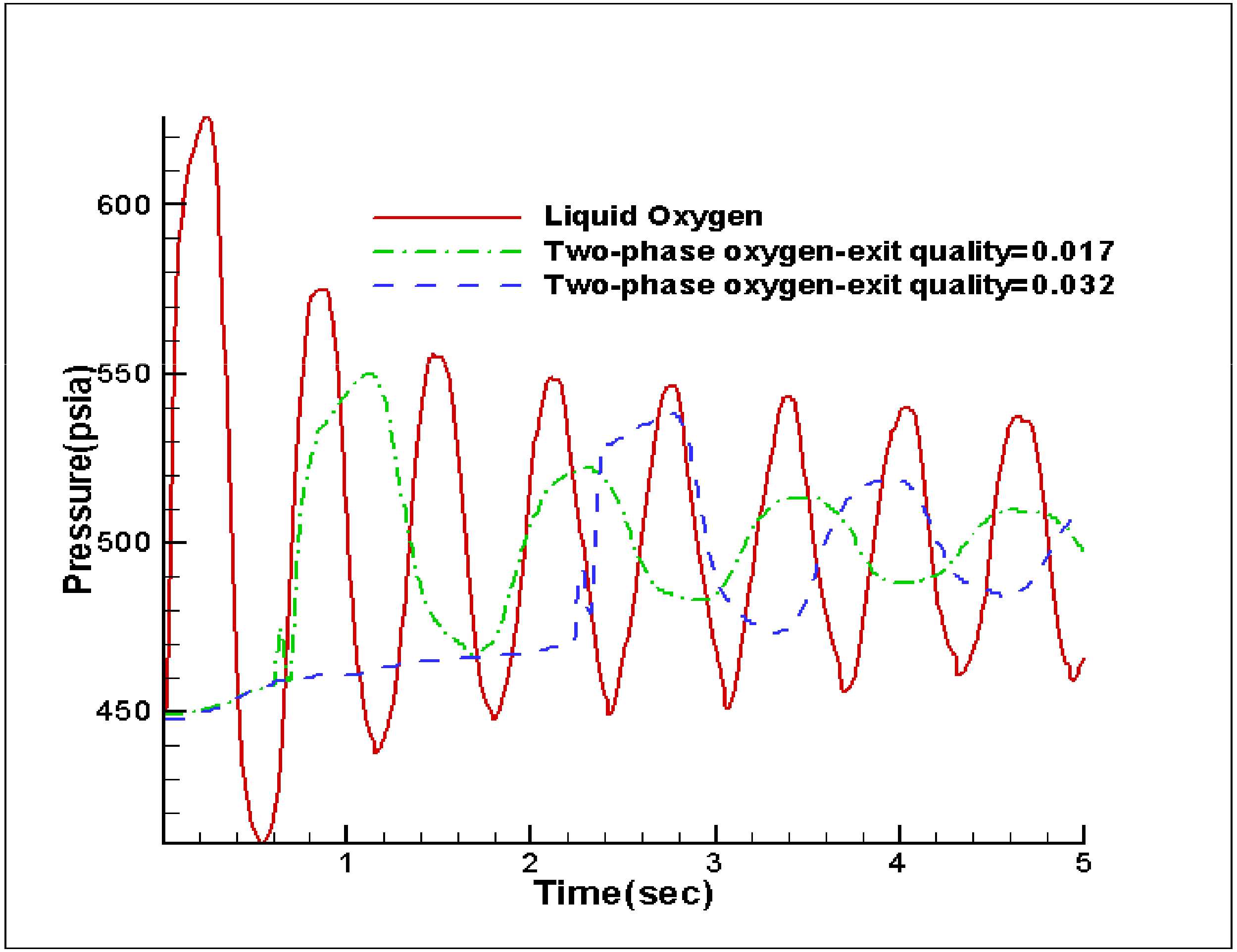
APPLICATIONS - 9

Fluid Transient in Two phase flow



APPLICATIONS - 10

Predicted Fluid Transient Due to Condensation



SUMMARY - 1

- GFSSP is a finite volume based Network Flow Analyzer
- Flow circuit is resolved into a network consisting of nodes and branches
- Mass, energy and specie conservation are solved at internal nodes. Momentum conservation is solved at branch
- Generalized data structure allows generation of all types of flow network
- Modular code structure allows to add new capabilities with ease

SUMMARY – 2

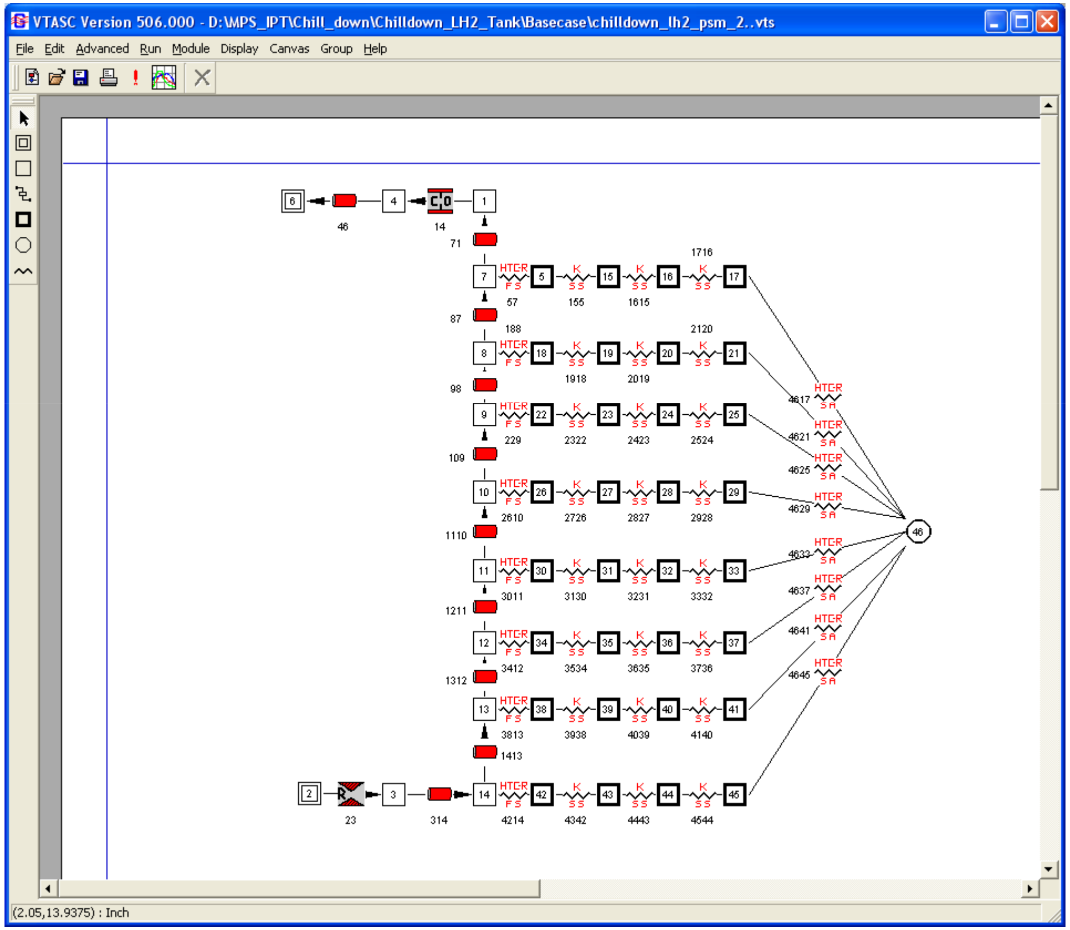
- Unique mathematical formulation allows effective coupling of thermodynamics and fluid mechanics
- Numerical scheme is robust; adjustment of numerical control parameters is seldom necessary
- Intuitive Graphical User Interface makes it easy to build, run and evaluate numerical models
- GFSSP has been successfully applied in various applications that included
  - Incompressible & Compressible flows
  - Phase change (Boiling & Condensation)
  - Fluid Mixture
  - Thermodynamic transient (Pressurization & Blowdown)
  - Fluid Transient (Waterhammer)
  - Conjugate Heat Transfer

SUMMARY – 3

- GFSSP is available from NASA/MSFC's Technology Transfer Office for US Government agencies and contractors
- An Audio-Video Training Course is also available
- More information about the code and its methodology is available at

  http://gfssp.msfc.nasa.gov/

VTASC – AN INTERACTIVE PREPROCESSOR FOR GFSSP



BACKGROUND -1

Visual Thermo-fluid dynamic Analyzer for Systems and Components (VTASC) is a program designed to efficiently build flow network models for use in the GFSSP program.

- Visually Interactive
  - Eliminates pre-design of models
  - Immediate feedback on model
- Self-Documenting
  - Hard copy of flow network
  - Bitmap image of flow network for inclusion into papers and presentations

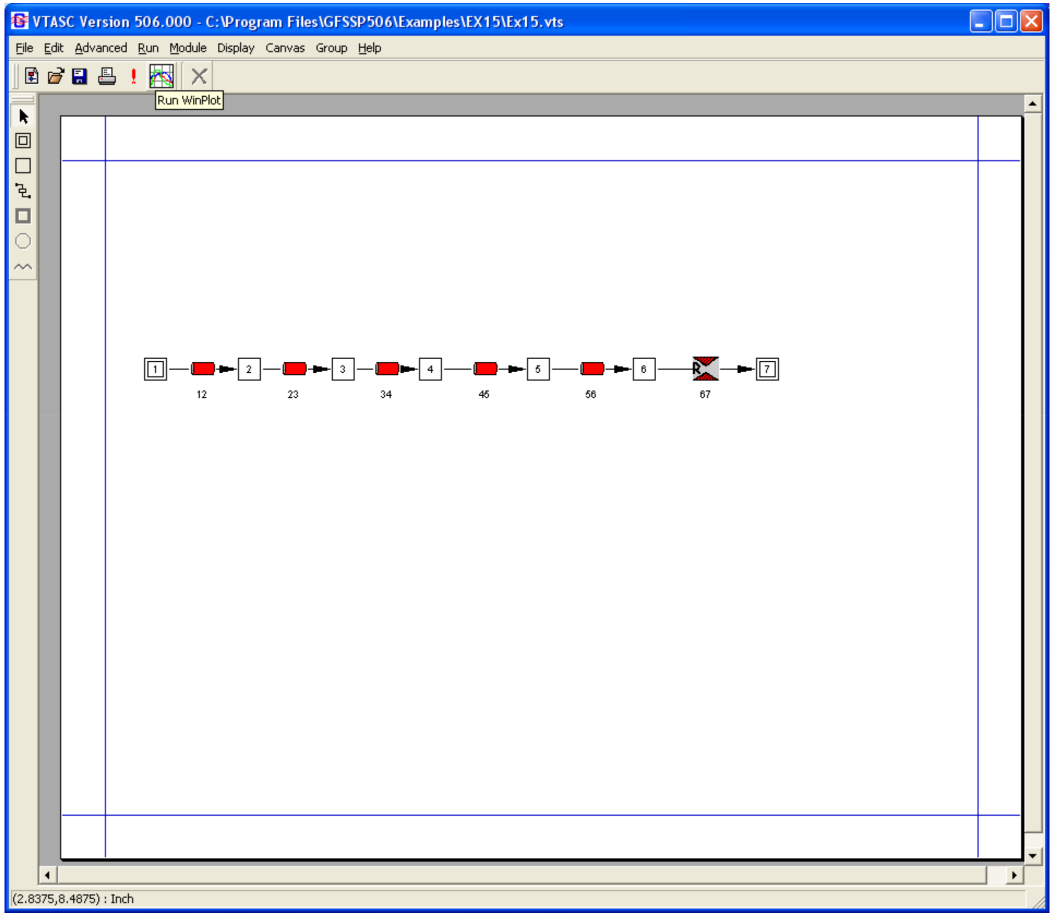
BACKGROUND -2

- Eliminates errors during model building process
  - Automatic node and branch numbering
  - Save and restore models at any point in the model building process
  - Robust
- Pushbutton generation of GFSSP input file
  - Steady and Transient cases
  - Advanced features such as Turbopump, Tank Pressurization and Heat Exchangers
- Run GFSSP directly from VTASC window
  - GFSSP Run Manager acts as VTASC/GFSSP interface

BACKGROUND -3

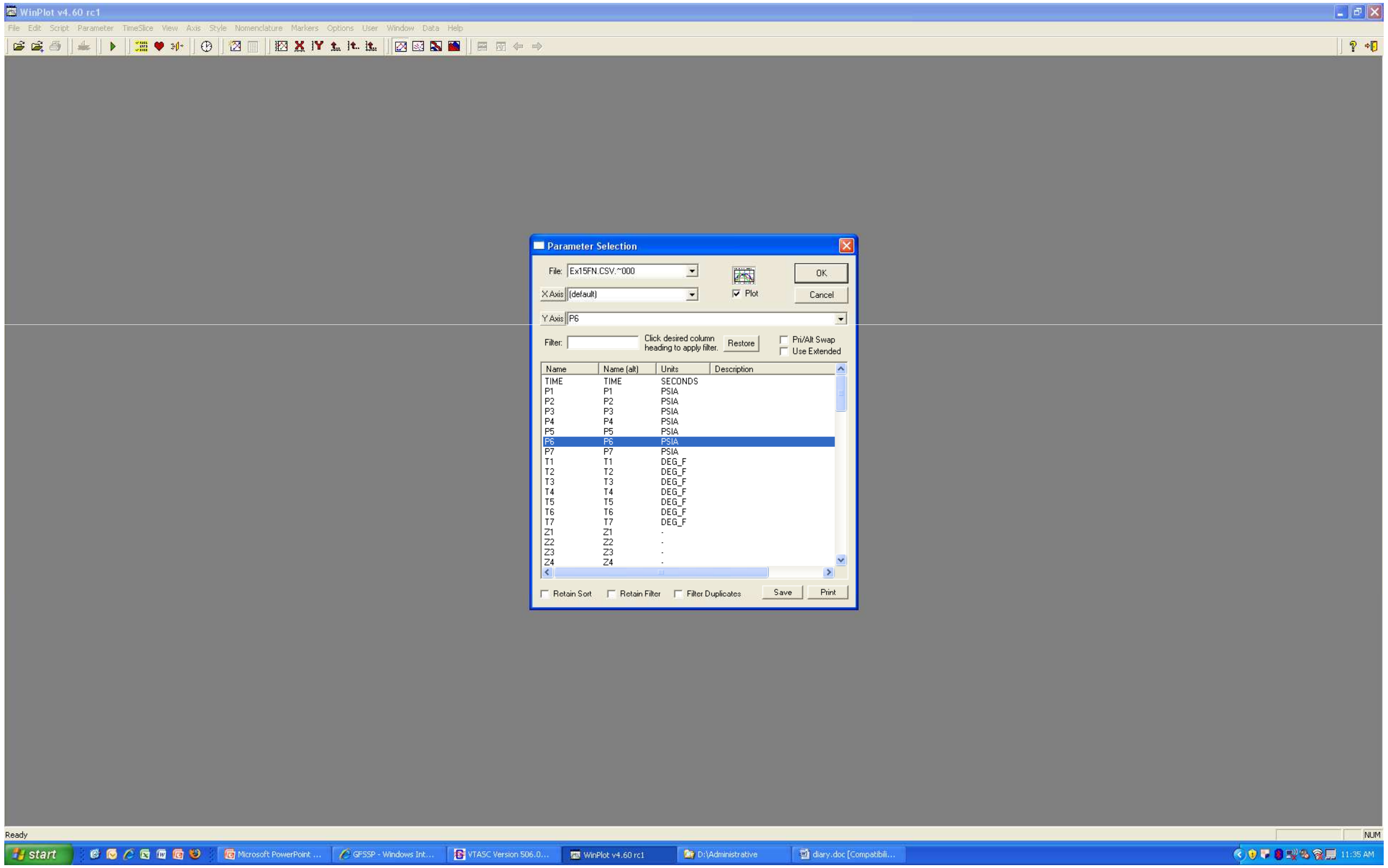
- Post-processing capability allows quick study of results
  - Pushbutton access to GFSSP output file
  - Point and click access to output at each node and branch
  - Built-in plotting capability for transient cases
  - Capable of plotting through Winplot
- Cross platform operation
  - Program written in C++
  - Uses cross platform C++ GUI toolkit

CREATING A CHART IN WINPLOT

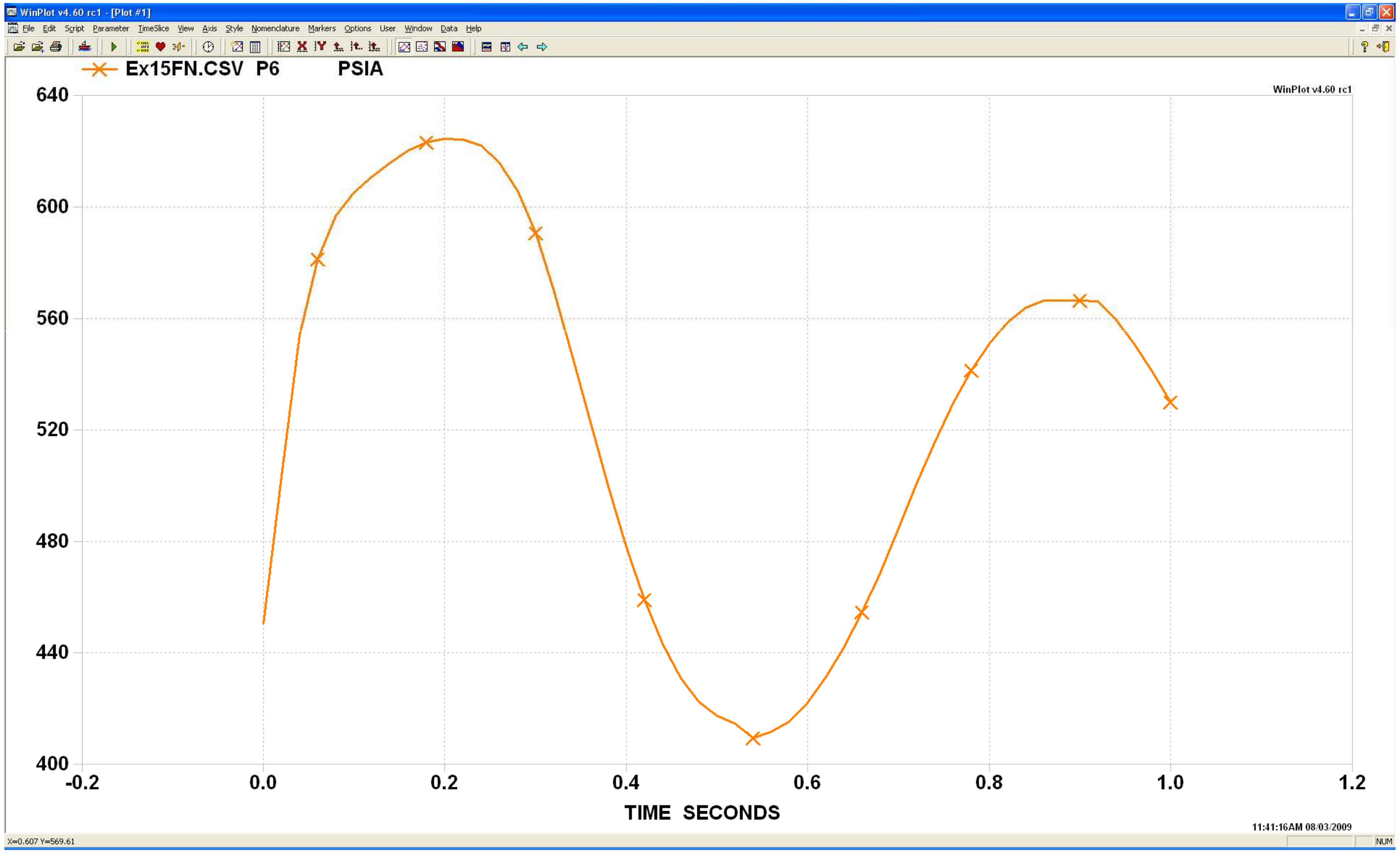


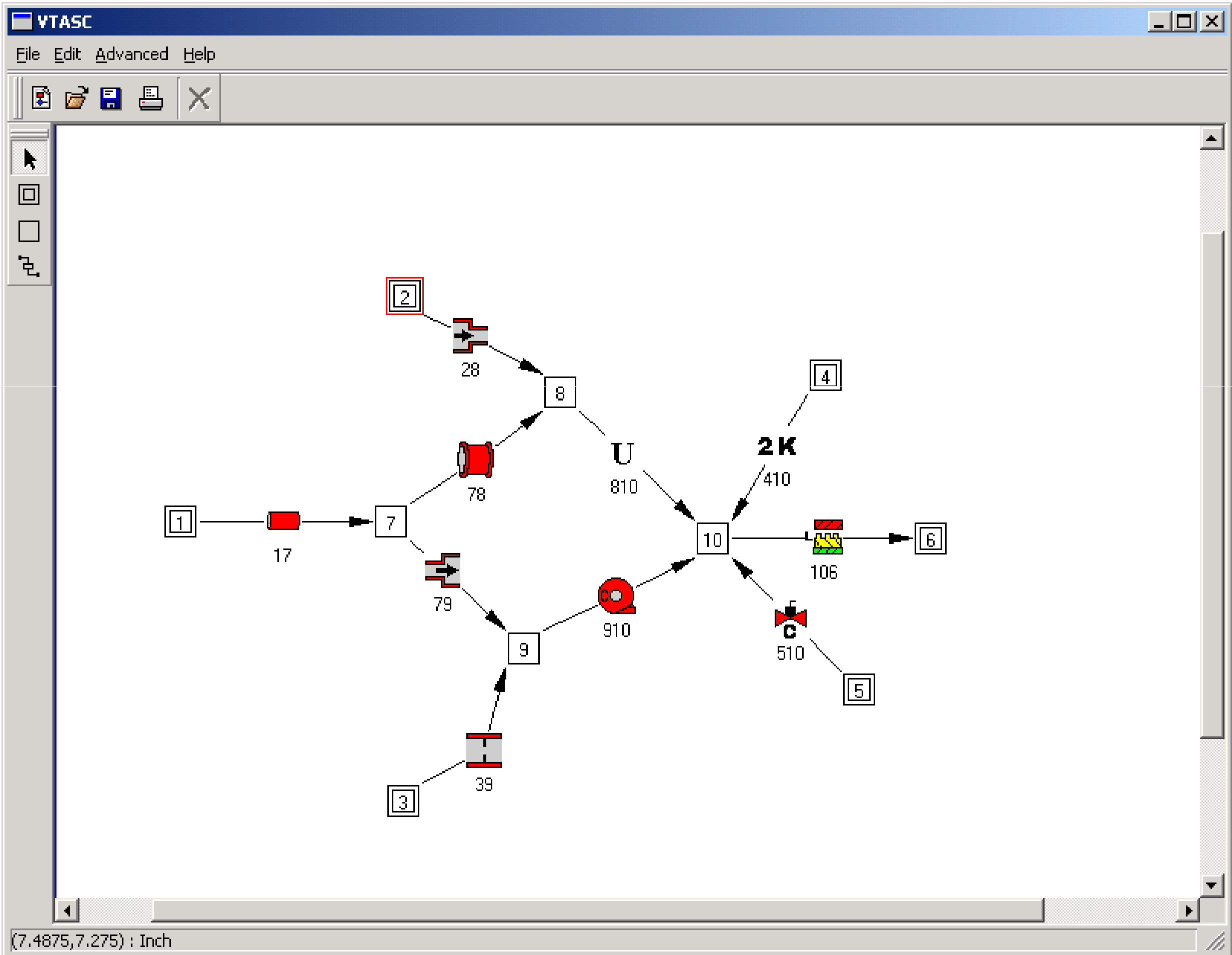
•After completing a model run, select Winplot from the VTASC Run Menu

CREATING A CHART IN WINPLOT

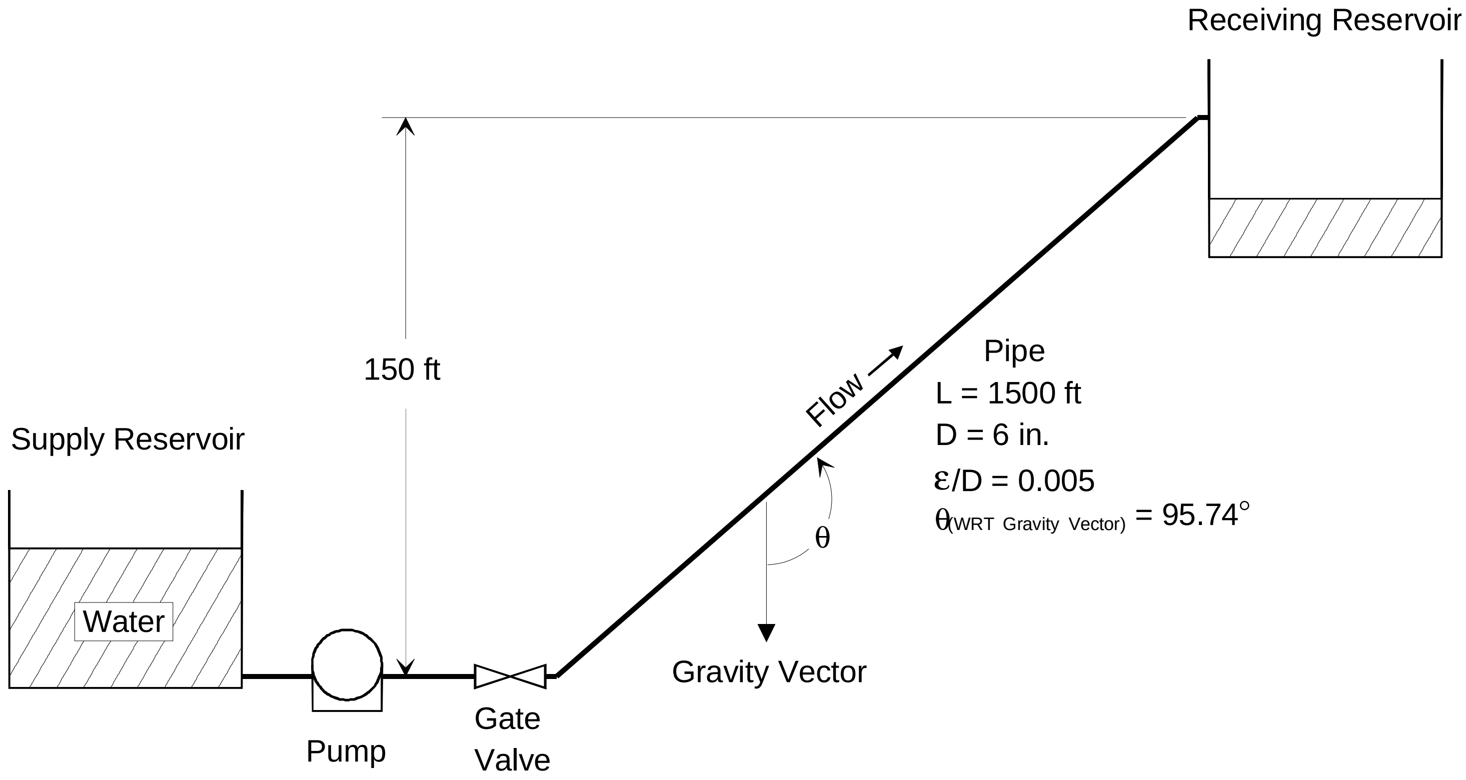


CREATING A CHART IN WINPLOT

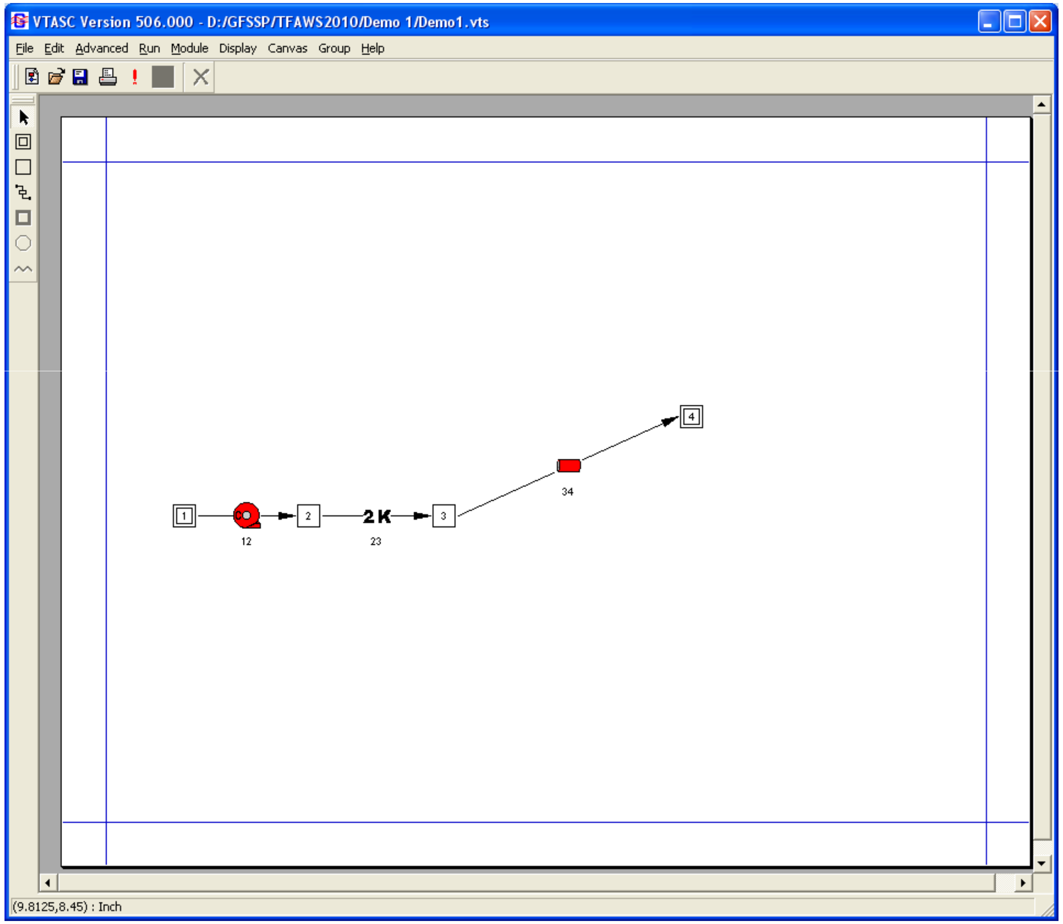



VTASC
File Edit Advanced Help
2
28
8
4
U
810
2K
410
1
17
7
78
10
106
6
79
910
9
510
5
39
3
(7.4875,7.275) : Inch

VTASC DEMONSTRATION PROBLEMS -1

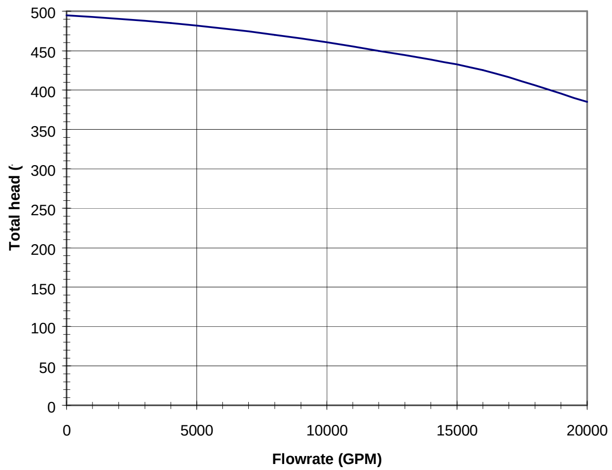


Demo 1:
Build Model on VTASC Canvas



$\dot{m}$

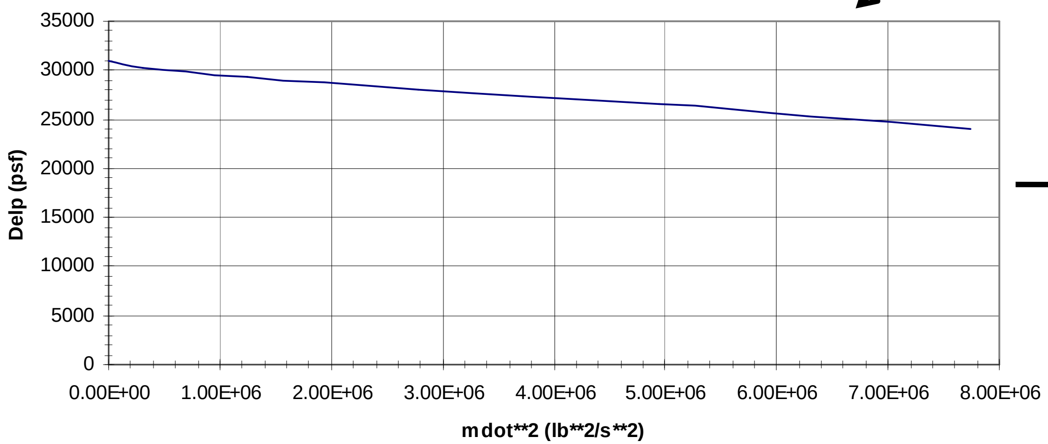
Demo 1:
Determination of Pump Characteristics



1.) Manufacturer’s Pump Curve (Head vs. Flowrate)

Q (GPM)	mdot (lb/s)	Head (ft)	Δp (psf)	$mdot^2$ $(lb/s)^2$
0	0	495	30,888	0
4000	556.13	485	30,264	3.093e05
8000	1112.3	470	29,328	1.2372e06
12000	1668.4	450	28,080	2.784e06
16000	2224.5	425	26,520	4.9484e06
20000	2781	385	24,024	7.734e06

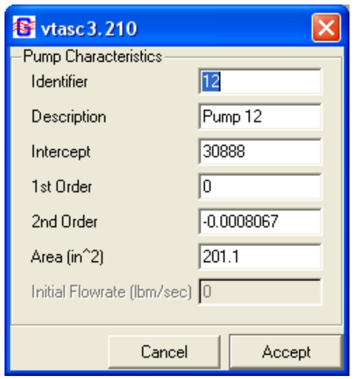
2.) Convert to lb/s and psf



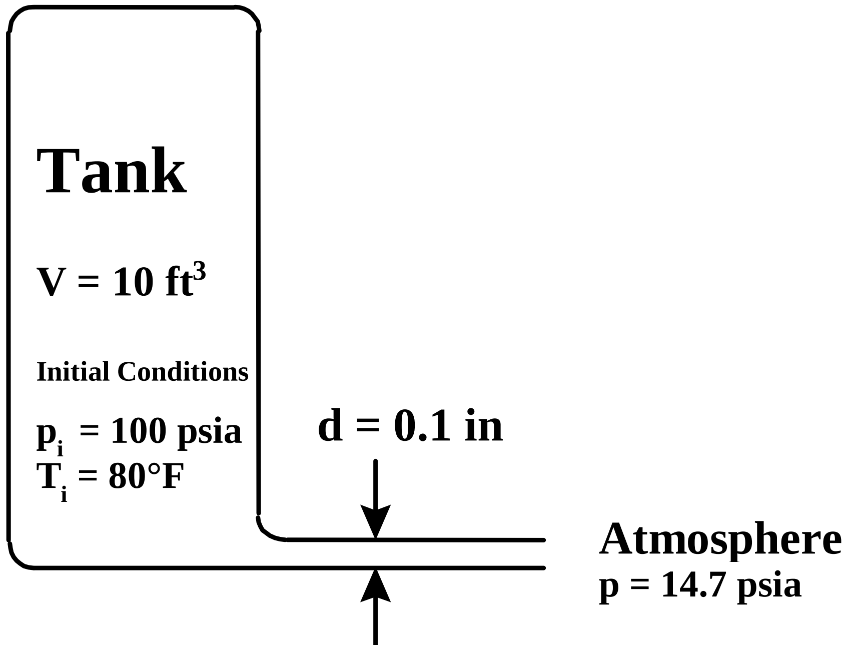
3.) Plot delP vs. $mdot^2$

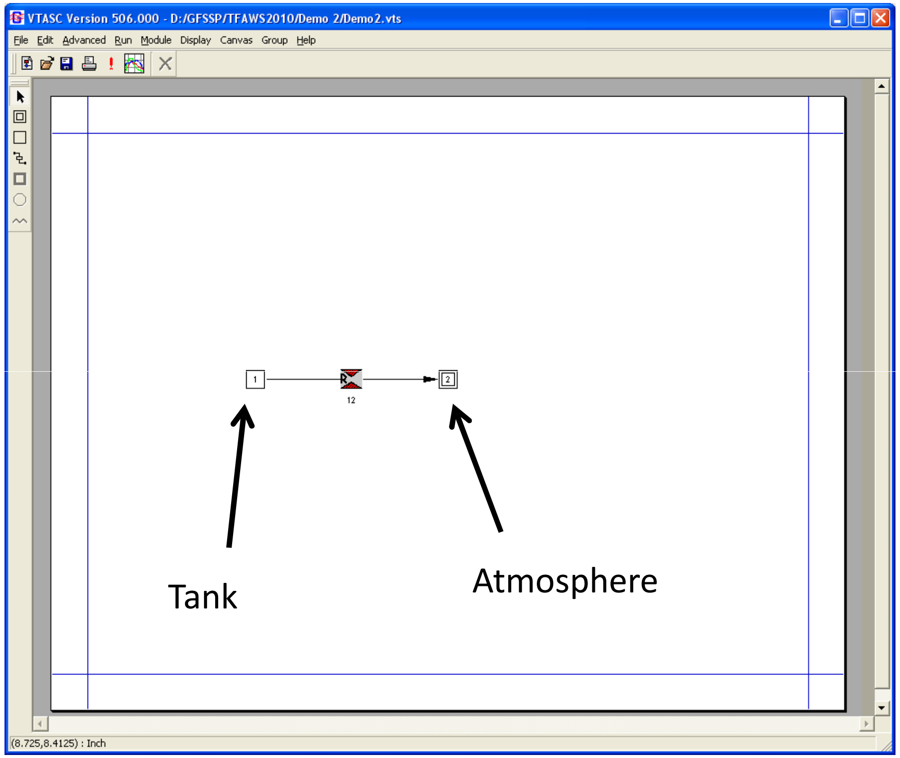
4.) Curve fit:

$$\Delta P = 30{,}888 - 8.067 \times 10^{-4}\, \dot{m}^2$$



VTASC DEMONSTRATION PROBLEMS -2

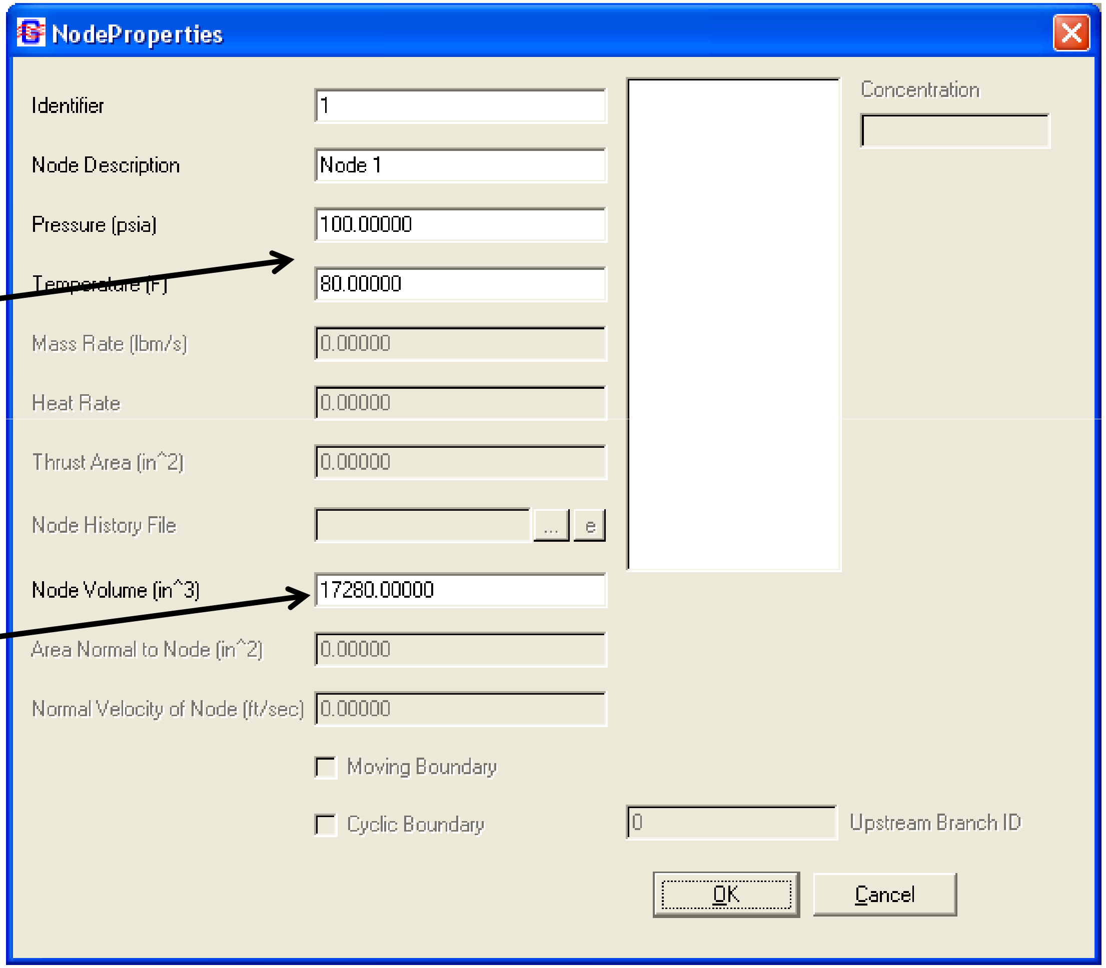




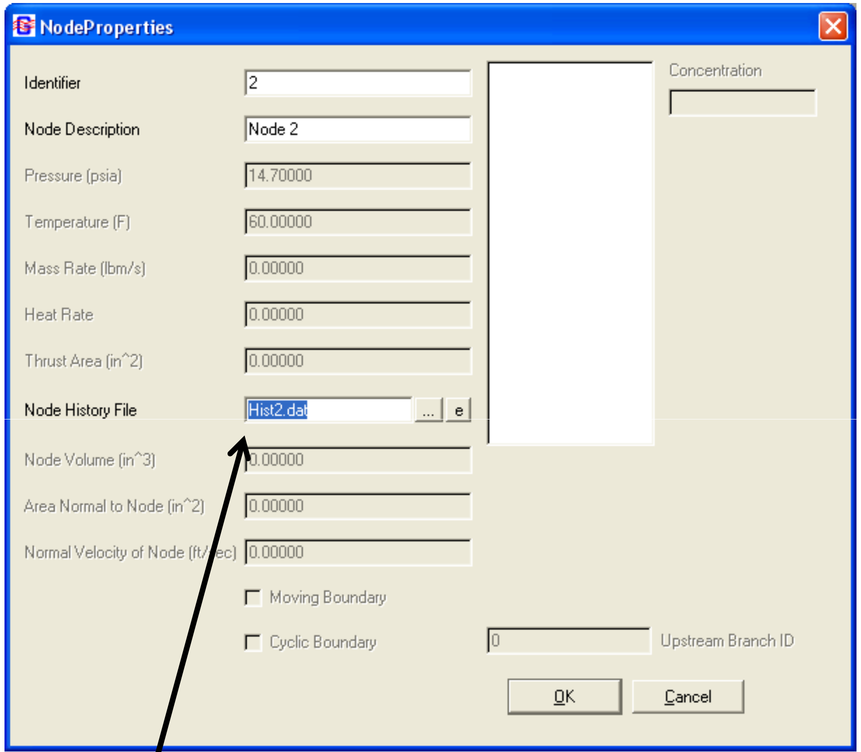
Demo 2:
Interior Node Initial Conditions

Initial P,T

Tank
Volume

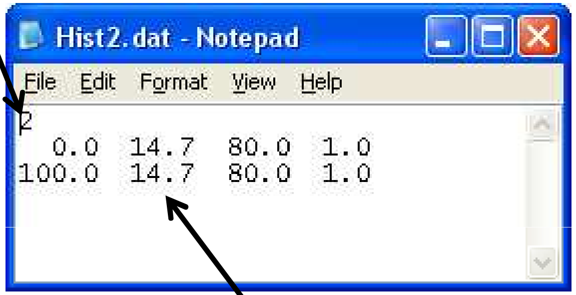


Demo 2:
Transient Boundary Conditions



Specify History Filename

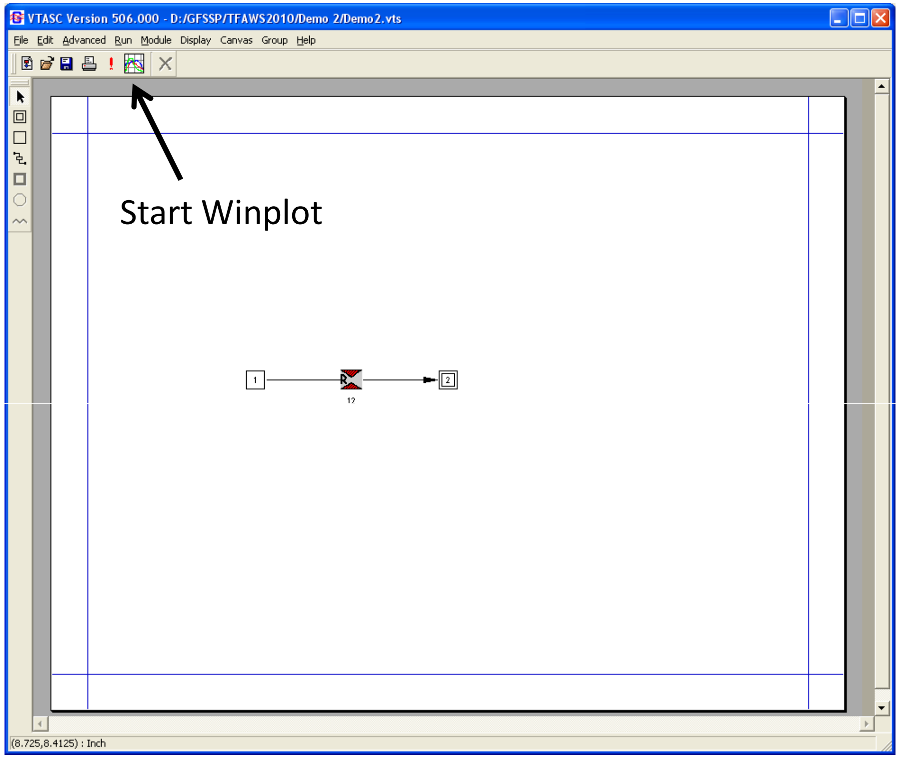
Number of Lines (min. 2)



Time (s), P(psia), T(F), Mass Fraction

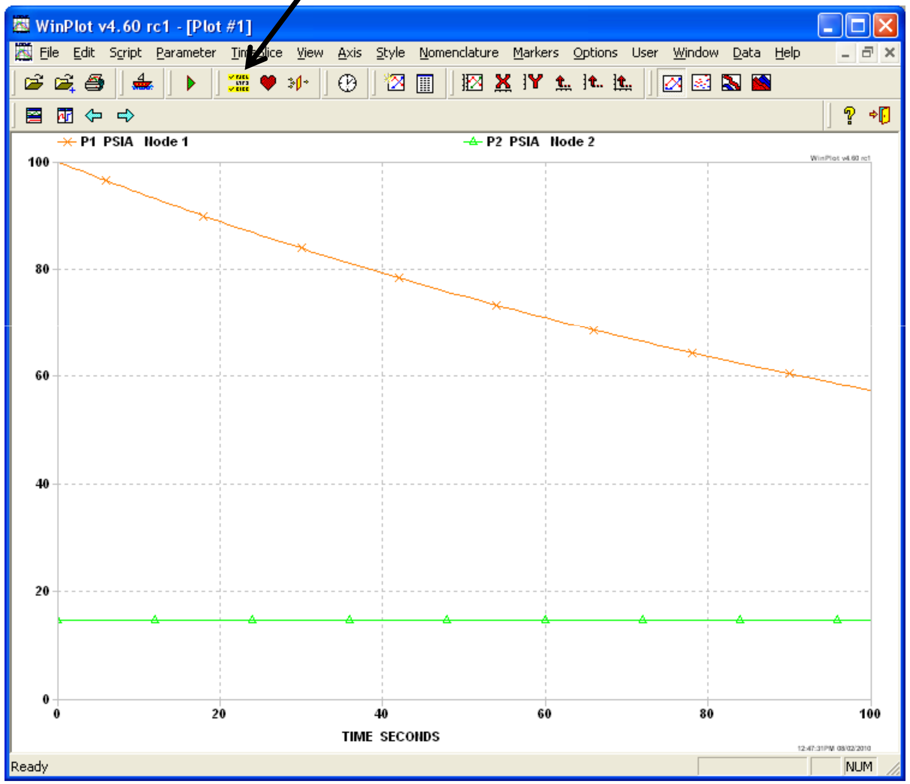
- GFSSP will interpolate transient boundary conditions from the history file
- Even if boundary conditions are constant, at least two lines must be given

Demo 2:
Plotting Transient Results



Start Winplot

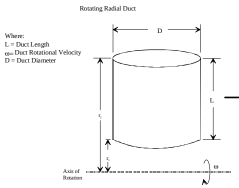
Select Parameters



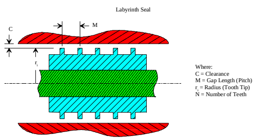
SUMMARY

- VTASC is a flow network model builder for use with GFSSP
- Flow networks can be designed and modified interactively using a "Point and Click" paradigm
- Generates GFSSP Version 4.0 compatible input files

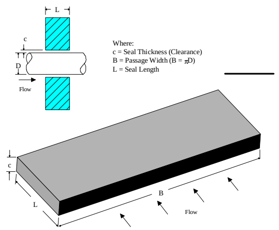
RESISTANCE & FLUID OPTIONS



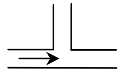
10. Rotating Radial Duct



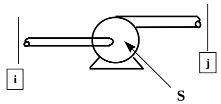
11. Labyrinth Seal



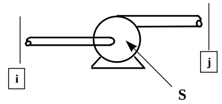
12. Face Seal



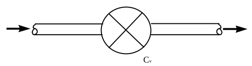
13. Common Fittings & Valves



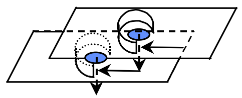
14. Pump Characteristics



15. Pump Power



16. Valve with Given Cv



17. Viscojet

RESISTANCE OPTIONS

$$\Delta P = K_f \dot{m}^2$$

GFSSP can model flow in the following passages:

- Circular and non-circular pipes/ducts
- Flow through a restriction
- Thick and thin orifice
- Square expansion and reduction
- Rotating radial and annular ducts
- Labyrinth Seal
- Flow between closely spaced parallel plates (Face Seals)
- Common fittings and valves
- Pump characteristics
- Pump power
- Joule-Thompson device
- Control Valve

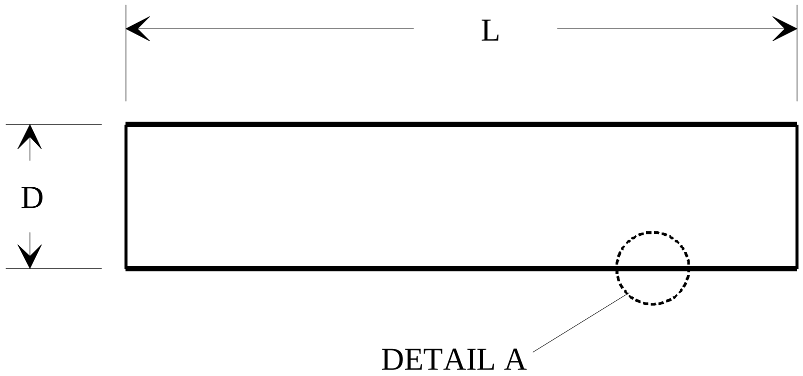
RESISTANCE OPTIONS

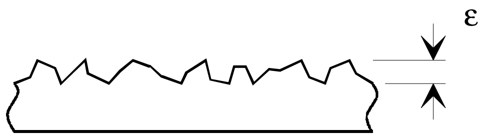
Option	Type of Resistance	Input Parameters	Option	Type of Resistance	Input Parameters
1	Pipe Flow	L (in), D (in), ε/D	10	Rotating Radial Duct	L (in), D (in), N (rpm)
2	Flow Through Restriction	C_L, A (in^2)	11	Labyrinth Seal	r_i (in), c (in), m (in), n, α
3	Non-circular Duct	a (in), b (in)	12	Flow Between Parallel Plates	r_i (in), c (in), L (in)
4	Pipe with Entrance and Exit Loss	L (in), D (in), ε/D, K_i, K_e	13	Common Fittings and Valves (Two K Method)	D (in), K_1, K_2
5	Thin, Sharp Orifice	D_1 (in), D_2 (in)	14	Pump Characteristics	A_0, B_0, A (in^2)
6	Thick orifice	L (in), D_1 (in), D_2 (in)	15	Pump Power	P (hp), η, A (in^2)
7	Square Reduction	D_1 (in), D_2 (in)	16	Valve with Given C_v	C_v , A
8	Square Expansion	D_1 (in), D_2 (in)	17	Joule-Thompson Device	L_{ohm}, V_f, k_v, A
9	Rotating Annular Duct	L (in), r_o (in), r_i (in), N (rpm)	18	Control Valve	See Example 12 data file

RESISTANCE OPTION 1

Pipe Resistance Option Parameters

PIPE FLOW





DETAIL A

Where:
D = Pipe Diameter
L = Pipe Length
ε = Absolute Roughness

Flow Resistance Factor Calculated from:

$$K_f = \frac{8\,fL}{\rho_u\,\pi^2\,D^5\,g_c}$$

For Re < 2300, Friction Factor is:

$$f = \frac{64}{\mathrm{Re}_D}$$

For Re > 2300, Friction Factor calculated from the Colebrook Equation:

$$\frac{1}{\sqrt{f}} = -2\log\left[\frac{\varepsilon}{3.7D} + \frac{2.51}{\mathrm{Re}\sqrt{f}}\right]$$

RESISTANCE OPTION 2

FLOW THROUGH A RESTRICTION

$$K_f = \frac{1}{2 g_c \rho_u C_L^2 A^2}$$

In Classical Fluid Mechanics, Head Loss, H, is Expressed as”.

$$\Delta H = K \frac{u^2}{2g}$$

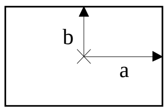
K and CL are Related by: $$C_L = \frac{1}{\sqrt{K}}$$

If the User sets C_L to 0, the code will set K_f to 0 (invisid flow through the branch)

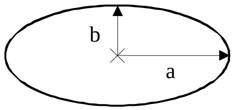
RESISTANCE OPTION 3

NON-CIRCULAR DUCT

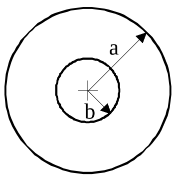
Four cross-sections currently considered:



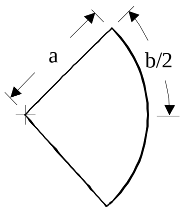
(a) - Rectangle



(b) - Ellipse

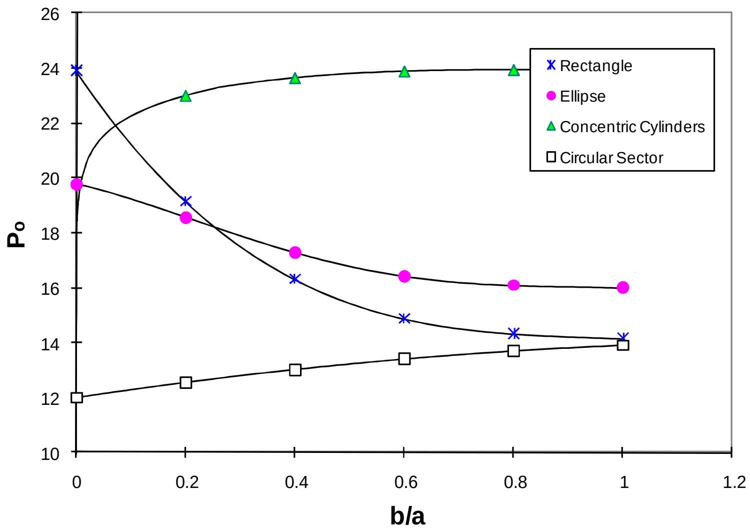


(c) - Concentric Annulus



(d) - Circular Sector

Poiseuille Number Relationship For Laminar Flow



RESISTANCE OPTION 3 - CONTINUED

NON-CIRCULAR DUCT - CONTINUED

Reynolds Number based upon Hydraulic Diameter D_h (= 4A/P)

Laminar Flow **(Re_{D_h} < 2300)**

$$f = \frac{4Po}{Re_{D_h}}$$

Turbulent Flow **(Re_{D_h} > 2300)**

1. Compute Effective Diameter

$$D_{eff} = \frac{16D_h}{Po}$$

2. Compute Effective Reynolds Number

$$Re_{eff} = \frac{\dot{m}}{\mu}\frac{D_{eff}}{A}$$

3. Use Effective Diameter & Reynolds Number in Colebrook Equation:

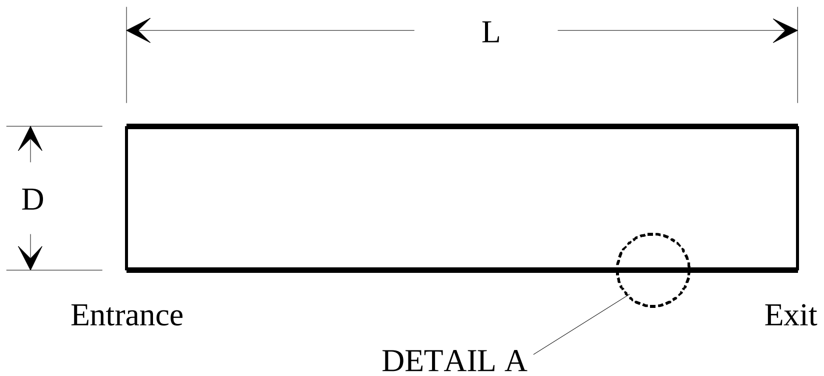
$$\frac{1}{\sqrt{f}} = -2\log\left[\frac{\varepsilon}{3.7D} + \frac{2.51}{Re\sqrt{f}}\right]$$

Flow Resistance Factor Calculated from: $K_f = \dfrac{8fL}{\rho_u \pi^2 D_h^5 g_c}$

RESISTANCE OPTION 4

PIPE FLOW WITH ENTRANCE AND EXIT LOSS

Pipe With Entrance and/or Exit Loss



DETAIL A

Where:

D = Pipe Diameter

L = Pipe Length

ε = Absolute Roughness

K_i = Entrance Loss Coefficient

K_e = Exit Loss Coefficient

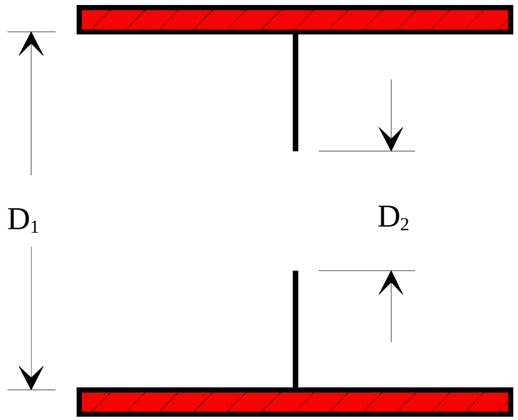
Flow Resistance Factor:

$$K_f = \frac{8K_i}{\rho_u \pi^2 D^4 g_c} + \frac{8 f L}{\rho_u \pi^2 D^5 g_c} + \frac{8K_e}{\rho_u \pi^2 D^4 g_c}$$

RESISTANCE OPTION 5

THIN SHARP ORIFICE

Thin Sharp Orifice



Where:
D_1 = Pipe Diameter
D_2 = Orifice Throat Diameter

Flow Resistance Factor:

$$K_f = \frac{K_1}{2 g_c \rho_u A^2}$$

Where:

$$K1 = \left[2.72 + \left(\frac{D_2}{D_1}\right)^2 \left(\frac{120}{Re_{D_1}} - 1\right)\right]\left[1 - \left(\frac{D_2}{D_1}\right)^2\right]\left[\left(\frac{D_1}{D_2}\right)^4 - 1\right] \quad \text{for } Re_{D_1} \le 2{,}500$$

$$K_1 = \left[2.72 - \left(\frac{D_2}{D_1}\right)^2 \left(\frac{4000}{Re_{D_1}}\right)\right]\left[1 - \left(\frac{D_2}{D_1}\right)^2\right]\left[\left(\frac{D_1}{D_2}\right)^4 - 1\right] \quad \text{for } Re_{D_1} > 2{,}500$$

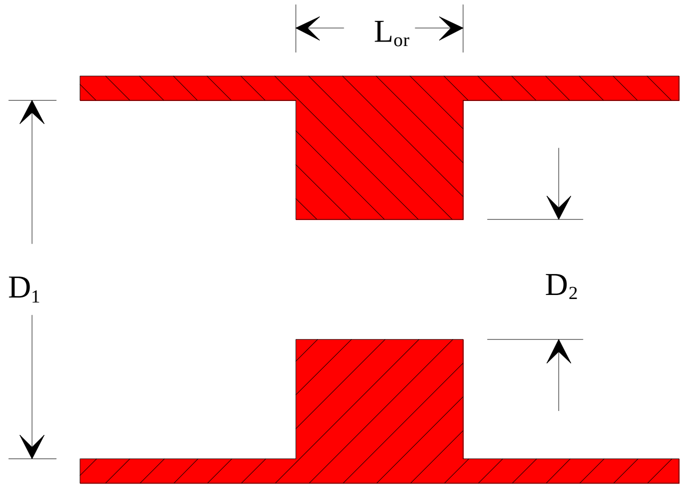
RESISTANCE OPTION 6

THICK ORIFICE

Flow Resistance Factor:

$$K_f = \frac{K_1}{2 g_c \rho_u A^2}$$

Thick Orifice



Where:
D_1 = Pipe Diameter
D_2 = Orifice Throat Diameter
L_{or} = Orifice Length

Where:

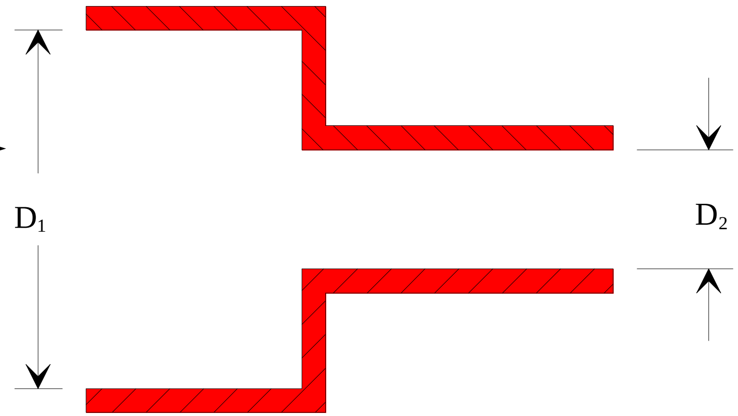
$$K_1 = \left[2.72 + \left(\frac{D_2}{D_1}\right)^2 \left(\frac{120}{Re_{D_1}} - 1\right)\right]\left[1 - \left(\frac{D_2}{D_1}\right)^2\right]\left[\left(\frac{D_1}{D_2}\right)^4 - 1\right]\left[0.584 + \frac{0.0936}{\left(L_{or}/D_2\right)^{1.5} + 0.225}\right] \quad \text{for } Re_{D_1} \le 2{,}500$$

$$K_1 = \left[2.72 - \left(\frac{D_2}{D_1}\right)^2 \left(\frac{4000}{Re_{D_1}}\right)\right]\left[1 - \left(\frac{D_2}{D_1}\right)^2\right]\left[\left(\frac{D_1}{D_2}\right)^4 - 1\right]\left[0.584 + \frac{0.0936}{\left(L_{or}/D_2\right)^{1.5} + 0.225}\right] \quad \text{for } Re_{D_1} > 2{,}500$$

RESISTANCE OPTION 7

SQUARE REDUCTION

Square Reduction



Where:
D_1 = Upstream Pipe Diameter
D_2 = Downstream Pipe Diameter

Flow Resistance Factor:

$$K_f = \frac{K_1}{2 g_c \rho_u A^2}$$

Where:

$$K_1 = \left[1.2 + \frac{160}{Re_{D_1}}\right]\left[\left(\frac{D_1}{D_2}\right)^4 - 1\right] \qquad \text{for } Re_{D_1} \le 2{,}500$$

$$K_1 = \left[0.6 + 0.48f\right]\left(\frac{D_1}{D_2}\right)^2\left[\left(\frac{D_1}{D_2}\right)^2 - 1\right]^2 \qquad \text{for } Re_{D_1} > 2{,}500$$

RESISTANCE OPTION 8

SQUARE EXPANSION

Flow Resistance Factor:

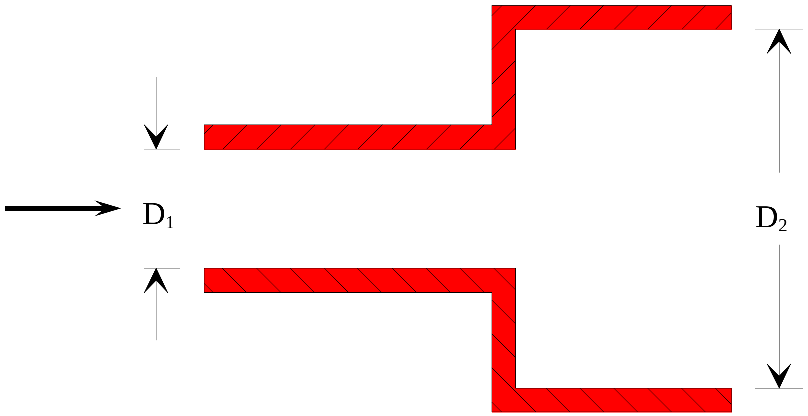
$$K_f = \frac{K_1}{2 g_c \rho_u A^2}$$

Where:

$$K_1 = 2\left[1 - \left(\frac{D_1}{D_2}\right)^4\right] \quad \text{for } Re_{D_1} \le 4{,}000$$

$$K_1 = [1 + 0.8f]\left[1 - \left(\frac{D_1}{D_2}\right)^2\right]^2 \quad \text{for } Re_{D_1} > 4{,}000$$

Square Expansion

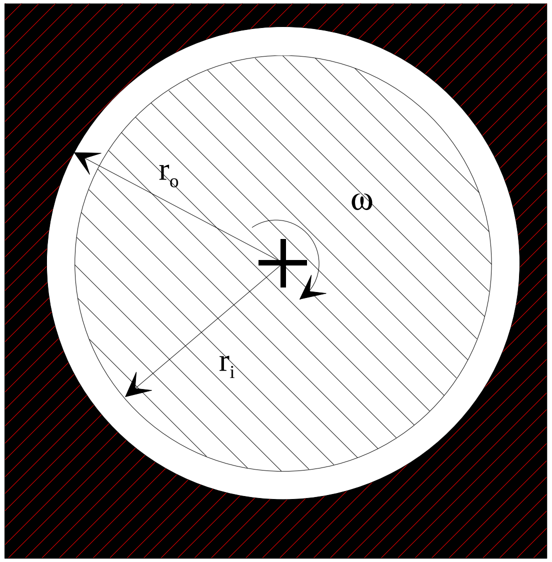


Where:
D_1 = Upstream Pipe Diameter
D_2 = Downstream Pipe Diameter

RESISTANCE OPTION 9

ROTATING ANNULAR DUCT

Rotating Annular Duct



Flow Resistance Factor:

$$K_f = \frac{f\ L}{\rho_u \pi^2\ A^2 g_c \left(r_o\ -\ r_i\right)}$$

Where:

$$\frac{f}{f_{0T}} = \left[1 + 0.7656\left(\frac{\omega\ r_i}{2u}\right)^2\right]^{0.38}$$

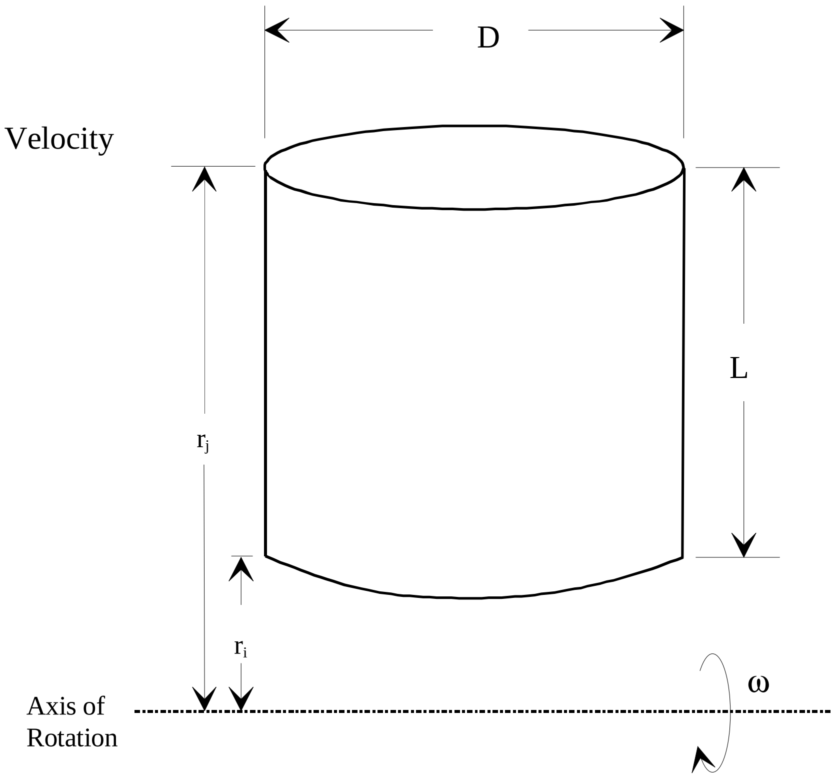
$$f_{0T} = 0.077\left(Ru\right)^{-0.24}, \qquad Ru = \frac{\rho_u u 2\left(r_o\ -\ r_i\right)}{\mu}$$

Where:
L = Duct Length (Perpendicular to Page)
b = Duct Wall Thickness ($b = r_o - r_i$)
ω = Duct Rotational Velocity
r_i = Duct Inner Radius
r_o = Duct Outer Radius

RESISTANCE OPTION 10

ROTATING RADIAL DUCT

Where:
L = Duct Length
ω= Duct Rotational Velocity
D = Duct Diameter



Flow Resistance Factor:

$$K_f = \frac{8 \, f \, L}{\rho_u \pi^2 D^5 g_c}$$

Where:

$$\frac{f}{f_{0T}} = 0.942 + 0.058\left[\left(\frac{\omega D}{u}\right)\left(\frac{\omega D^2}{\nu}\right)\right]^{0.282}$$

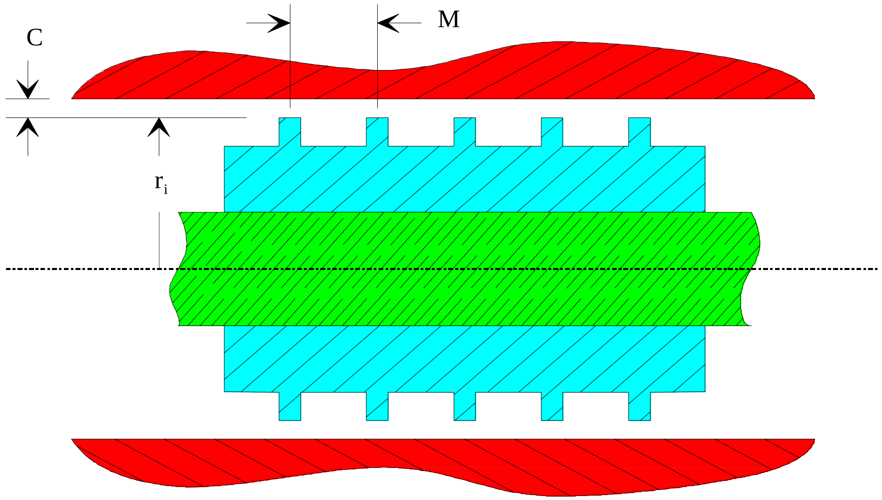
$$f_{0T} = 0.0791(\mathrm{Ru})^{-0.25}$$

$$\mathrm{Ru} = \frac{4\dot{m}}{\pi D \mu}$$

RESISTANCE OPTION 11

LABYRINTH SEAL

Labyrinth Seal



Where:
C = Clearance
M = Gap Length (Pitch)
r_i = Radius (Tooth Tip)
N = Number of Teeth
α = Step Seal Factor (~0.9)

Flow Resistance Factor (Modified Dodge Eqn):

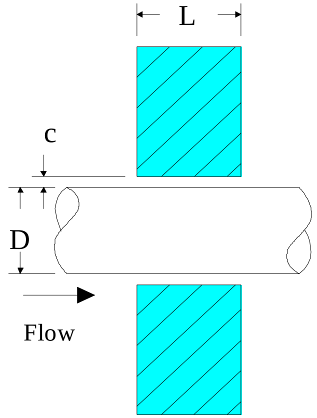
$$K_f = \frac{\left(\frac{1}{\varepsilon^2} + 0.5\right) N + 1.5}{2 g_c \rho_u \alpha^2 A^2}$$

Where:

$$\varepsilon = \sqrt{\frac{1}{\left\{1 - \left[\frac{C(N-1)/M}{N(\{C/M\} - 0.02)}\right]\right\}}}$$

RESISTANCE OPTION 12

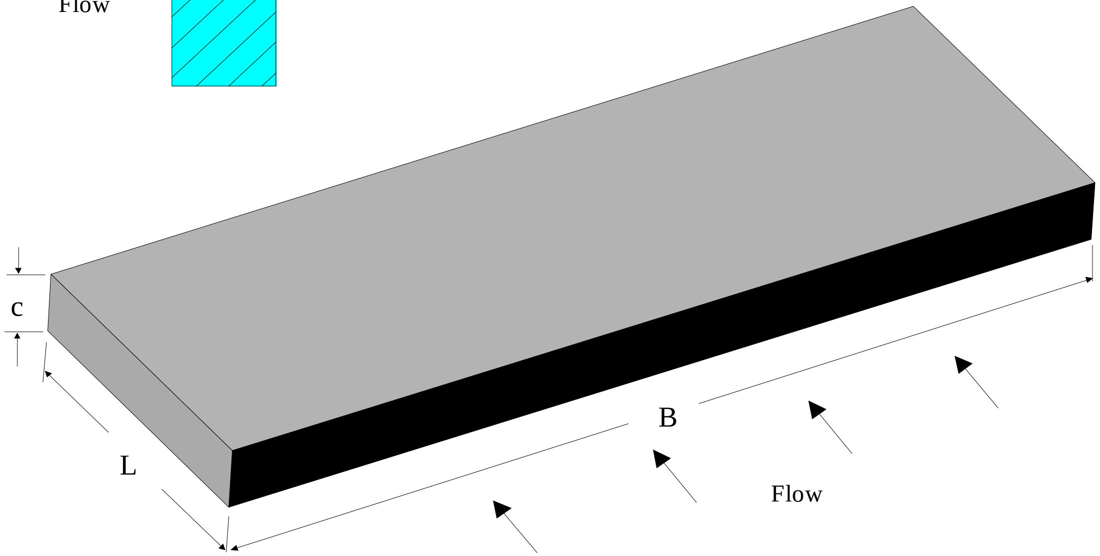
FACE SEAL



Where:
c = Seal Thickness (Clearance)
B = Passage Width (B = πD)
L = Seal Length

Flow Resistance Factor:

$$K_f = \frac{12\mu L}{\pi g_c D c^3 |\dot{m}| \rho}$$



RESISTANCE OPTION 13

COMMON FITTINGS AND VALVES

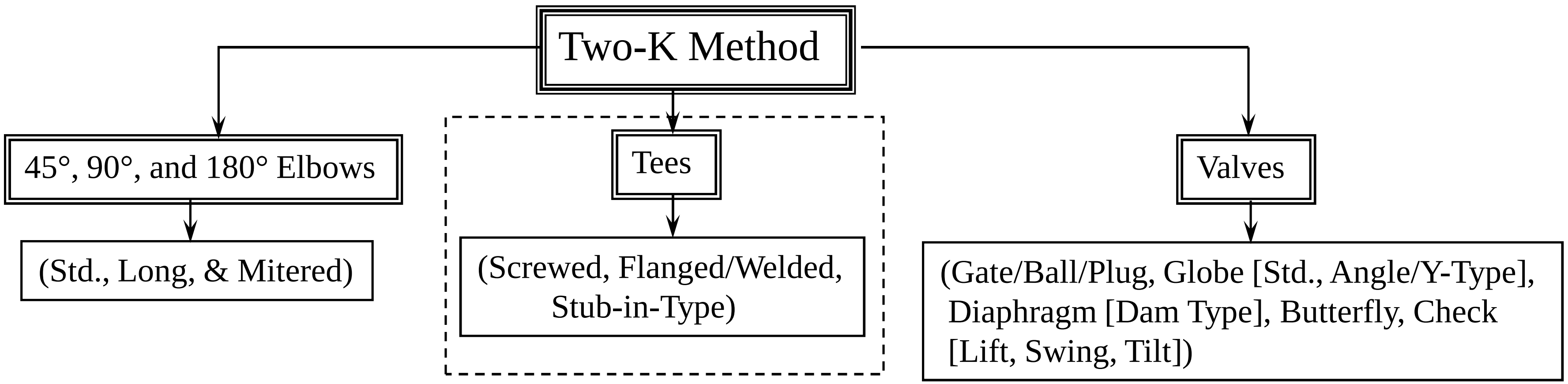
Flow Resistance Factor:

$$K_f = \frac{K_1 / \mathrm{Re} + K_\infty (1 + 1/D)}{2 g_c \rho_u A^2}$$

Where:

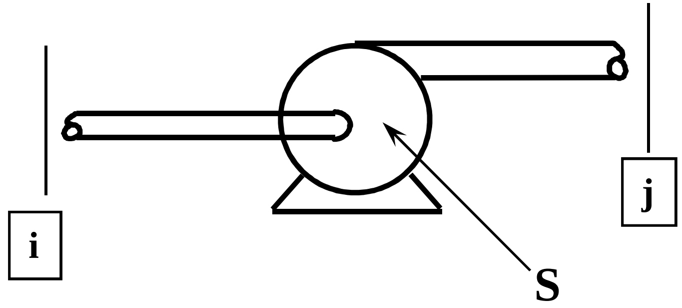
K_1 = K for the fitting at Re =1;
K_∞ = K for the fitting at Re = ∞ ; (K_2 in GFSSP)
D = Internal diameter of attached pipe, in.

The Following Common Fittings and Valves Can Be Modeled using This Option:



RESISTANCE OPTION 14

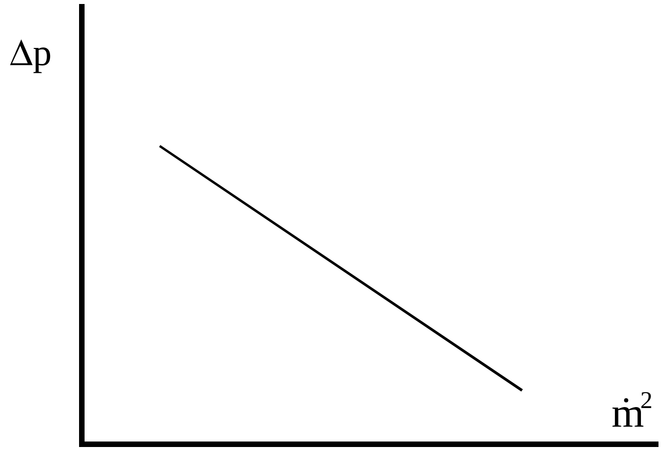
PUMP CHARACTERISTICS



This Option Considers the Branch as a Pump with Given Characteristics. The Pump Characteristics are Expressed in the Pressure Rise:

$$\Delta p = A_o + B_o \dot{m}^2$$

Where: Δp = Pressure Rise in lbf/ft^2
$\dot{m}$ = Flow Rate in lbm/sec

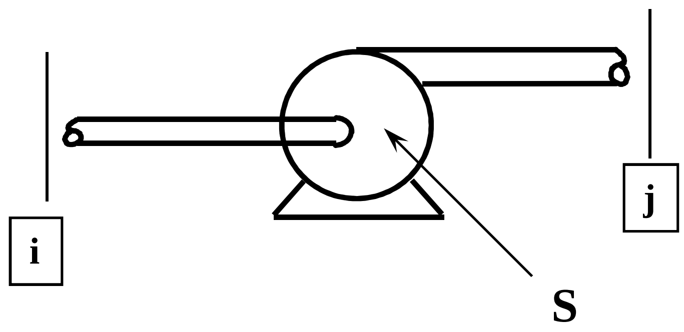


The Momentum Source Used to Induce the Desired Flow is:

$$S = \Delta p\, A$$

RESISTANCE OPTION 15

PUMP POWER

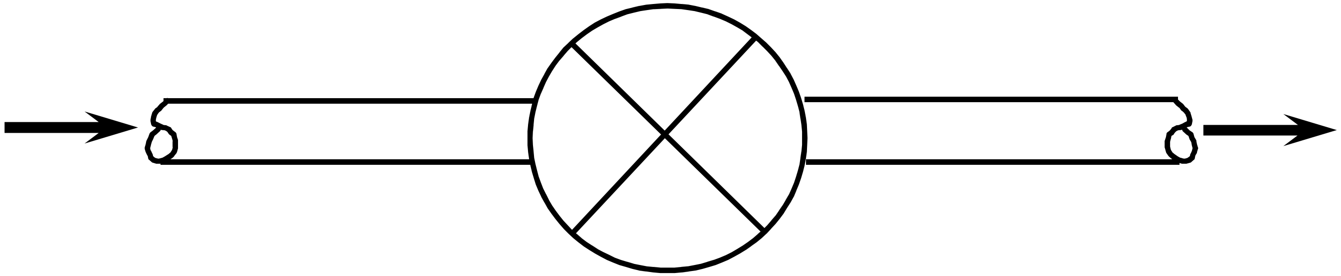


This Option Considers the Branch as a Pump with a Given Horsepower, P, and Efficiency, η. The Momentum Source, S, used to Induce the Desired Flow is Expressed as:

$$S = \frac{550\,\rho_u\,P\,\eta\,A}{\dot{m}}$$

RESISTANCE OPTION 16

VALVE WITH GIVEN CV



This Option Considers the Branch as a Valve with a Given C_v.
The Flow Resistance Factor for this Branch is Expressed as:

$$C_v = Q_{H_2O}\sqrt{\frac{1}{\Delta P_{H_2O}}} \qquad K_f = \frac{4.6799 \times 10^5}{\rho_u C_v^2}$$

RESISTANCE OPTION 17

VISCOJET (JOULE-THOMPSON DEVICE)

This option considers the branch as a Visco Jet which is a specific type of flow resistance with relatively large flow passages with very high pressure drops. The flow rate through the Visco Jet is given by:

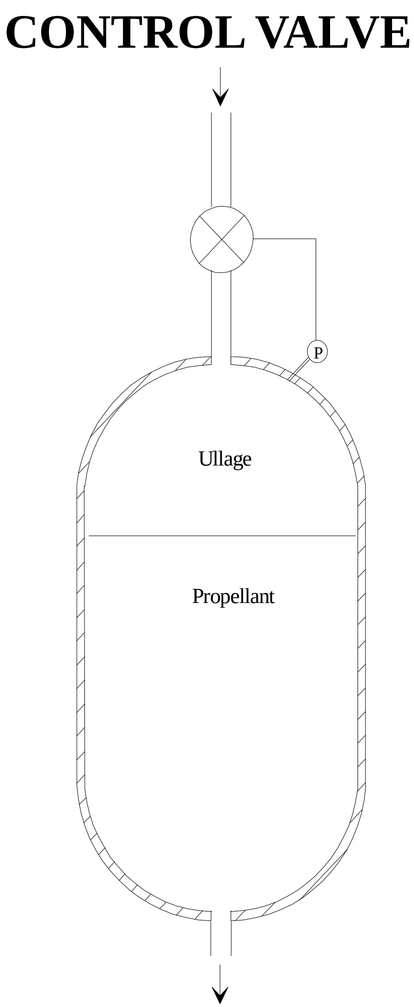
$$w = 10000\, k_v \frac{V_f}{L_{ohm}} \sqrt{\Delta p\, S.G.}\, (1 - x)$$

Where: w = the flow rate in lbm/hr,
L_{ohm} = the resistance of the fluid device $\left(\frac{\sqrt{lb_f / in^2}}{lb_m / hr}\right)$,
k_v = an empirical factor,
S.G. = Specific Gravity,
x = the downstream fluid quality, calculated by the code
and V_f = the viscosity correction factor.

For this option, K_f can be expressed as:

$$K_f = \frac{18.6624}{S.G.}\left(\frac{L_{ohm}}{V_f k_v (1 - x)}\right)^2$$

RESISTANCE OPTION 18



- Pressure monitored at arbitrary point downstream of valve
- Valve maintains pressure within user specified tolerance
  - Closes when pressure exceeds maximum value
  - Opens when pressure drops below minimum value
- Flow resistance factor calculated using same equations as Option 2

RESISTANCE OPTION 18 - CONTINUED

SUB-OPTIONS

- Instantaneous - Valve is either fully open or fully closed at any given time.
- Linear - Valve open/close transient is modeled as a linear operation.
- Non-linear - Valve open/close transient is modeled as some user specified non-linear operation.

RESISTANCE OPTIONS SUMMARY

- Most fluid systems can be modeled using available options
- Option 2 can be used as a generic option where C_L must be computed from a known pressure drop vs. flowrate characteristics.
- Flow situations with variable C_L must be modeled through User Subroutine.

FLUID OPTIONS

- GFSSP requires the following thermodynamic and thermophysical properties of fluids for the solution of the governing equations:
  - Density [$\rho(T, p)$]
  - Absolute Viscosity [$\mu(T, p)$]
  - Thermal Conductivity [$k(T, p)$]
  - Specific Heat at Constant Pressure [$C_p(T, p)$]
  - Ratio of Specific Heats [$\gamma(T, p)$]

- GFSSP requires these properties at every node at each iteration. These properties are supplied by thermodynamic property programs integrated into GFSSP.

AVAILABLE FLUIDS IN GASP/WASP

Working Fluid
Argon
Carbon Monoxide
Carbon Dioxide
Fluorine
Helium
Hydrogen
Methane
Neon
Nitrogen
Oxygen
Water
Kerosene (RP-1)
User Defined (Constant Property Fluid)

Properties Calculated Using: GASP & WASP

Properties Found in Lookup Table

User Supplies ρ and μ

(NOTE: The Energy Equation cannot be used with this Fluid Option)

AVAILABLE FLUIDS IN GASPAK

- **User can choose GASPAK by setting ADDPROP to TRUE and using User Subroutines**
- **GASPAK has a library of 32 fluids as well as an ideal gas option**

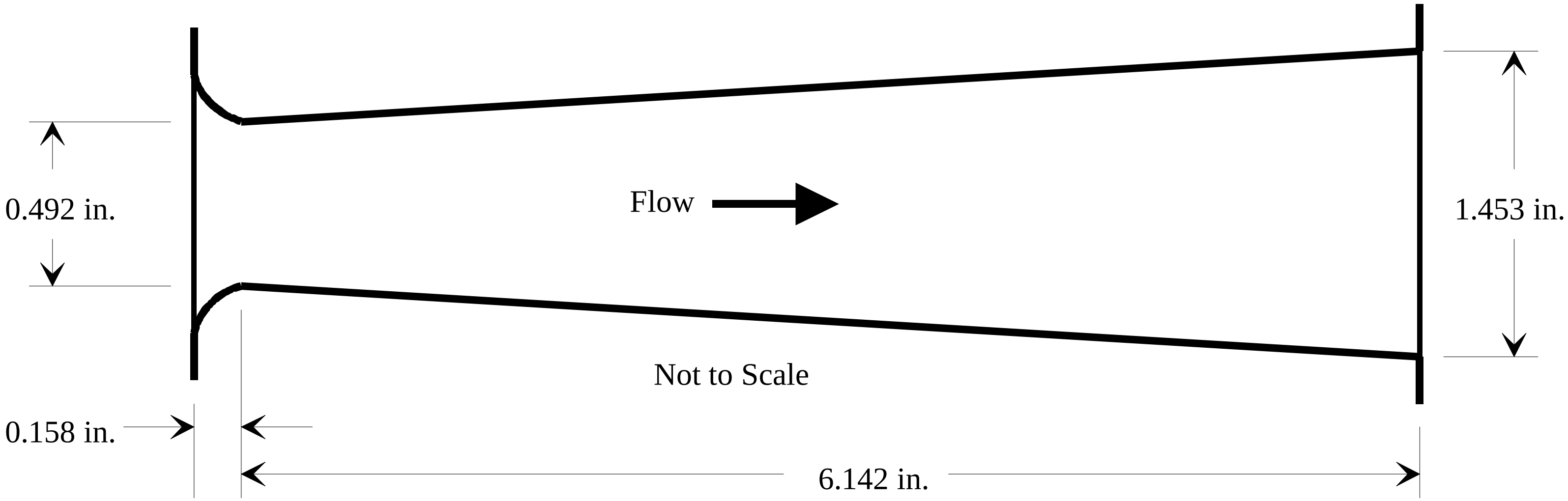
Index	Fluid	Index	Fluid
1	HELIUM	18	HYDROGEN SULFIDE
2	METHANE	19	KRYPTON
3	NEON	20	PROPANE
4	NITROGEN	21	XENON
5	CO	22	R-11
6	OXYGEN	23	R12
7	ARGON	24	R22
8	CO_2	25	R32
9	PARAHYDROGEN	26	R123
10	HYDROGEN	27	R124
11	WATER	28	R125
12	RP-1	29	R134A
13	ISOBUTANE	30	R152A
14	BUTANE	31	NITROGEN TRIFLUORIDE
15	DEUTERIUM	32	AMMONIA
16	ETHANE	33	IDEAL GAS
17	ETHYLENE		

FLUID OPTIONS SUMMARY

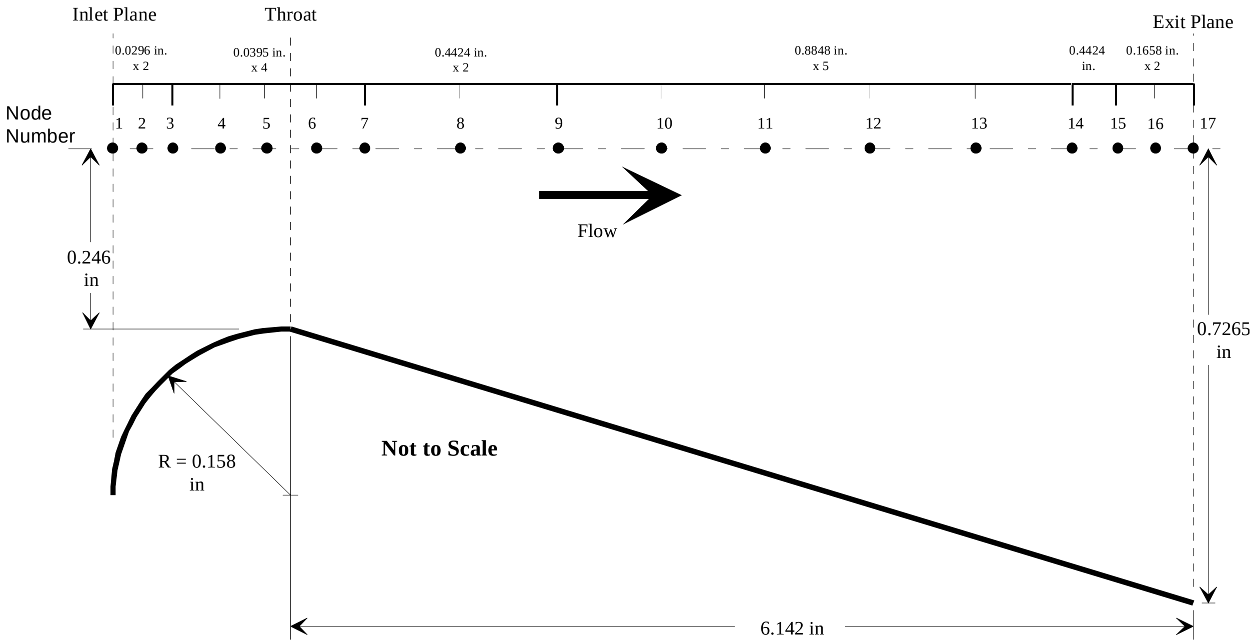
- GFSSP has a unified formulation for both gas and liquid
- Liquid is also modeled as compressible fluid with low compressibility factor
- GASP/WASP/GASPAK provide higher order equation of state to calculate properties of liquid and vapor state over a wide range
- Table look-up provision can be used to add new fluid to the library
- User Subroutines can also be used to generate properties for new fluids
- Universal Equation of State currently under development

Tutorial – 1

Simulation of Compressible Flow in a Converging-Diverging Nozzle



Converging-Diverging Nozzle Geometry



Problem Considered:

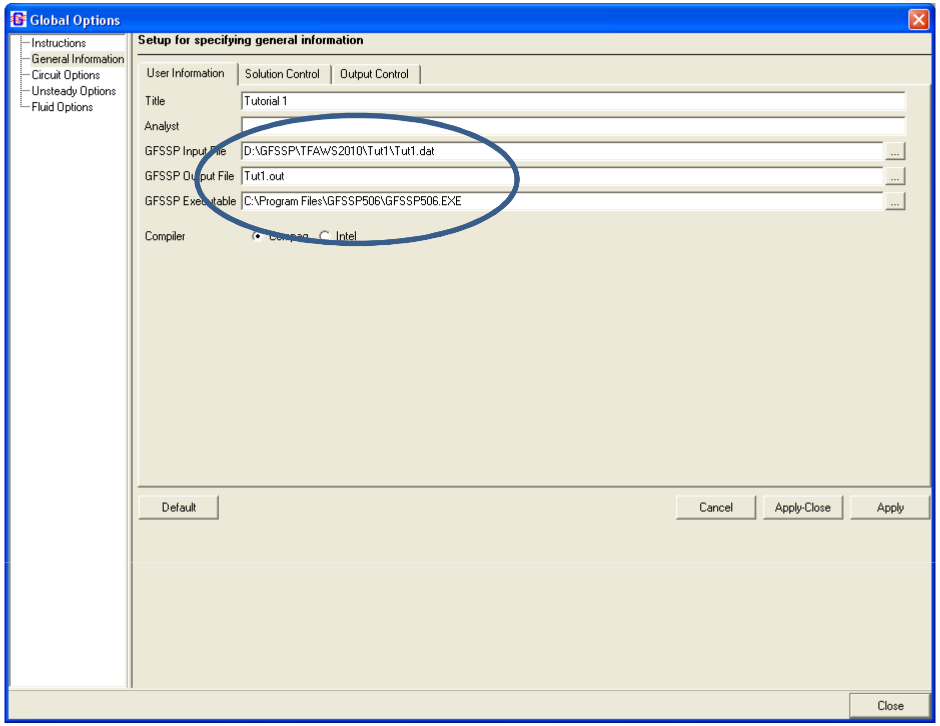
- One-dimensional pressure and temperature distribution
- Flow rates in subsonic and supersonic flow

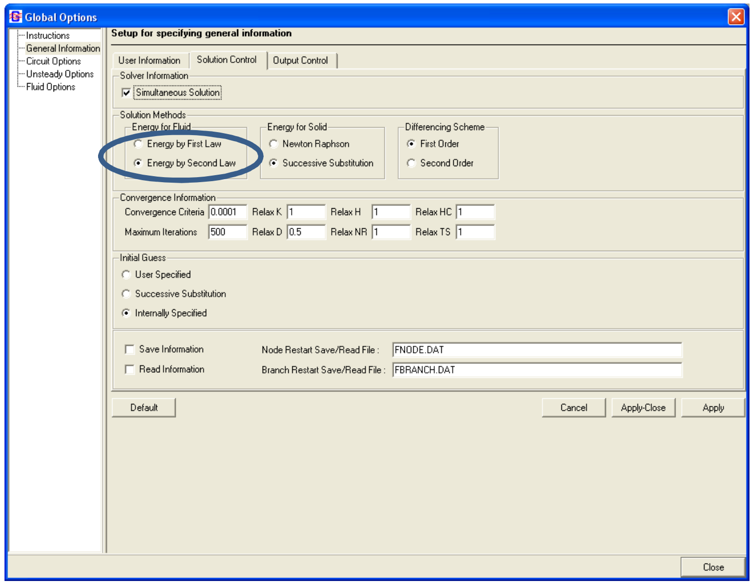
(This is a simplified version of Example 3 in the GFSSP User's Manual)

Program Options

Input data file : tut1.dat

Output data file : tut1.out



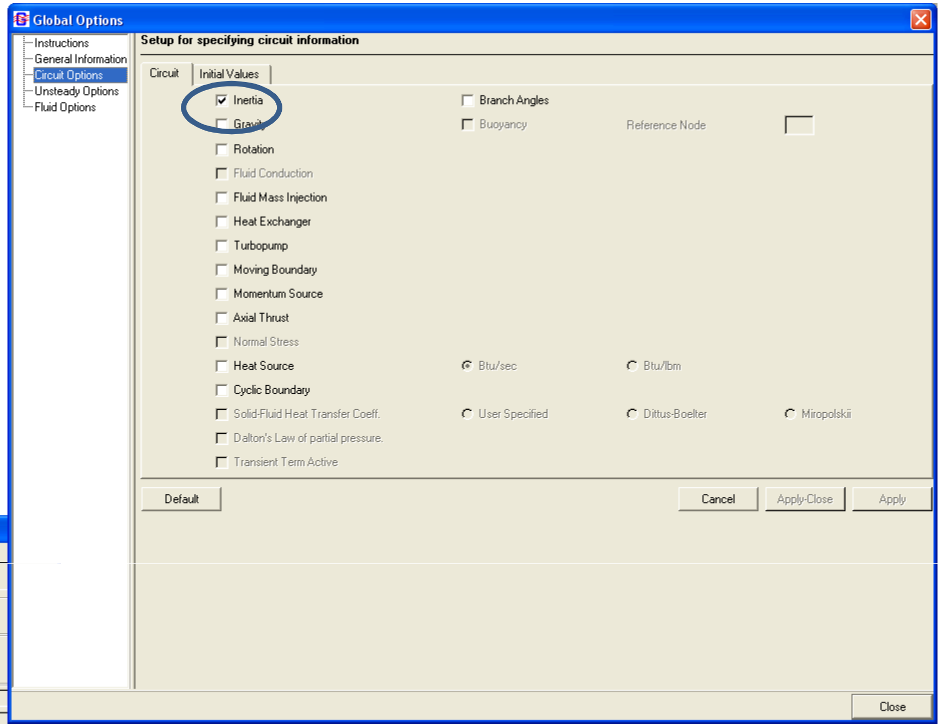


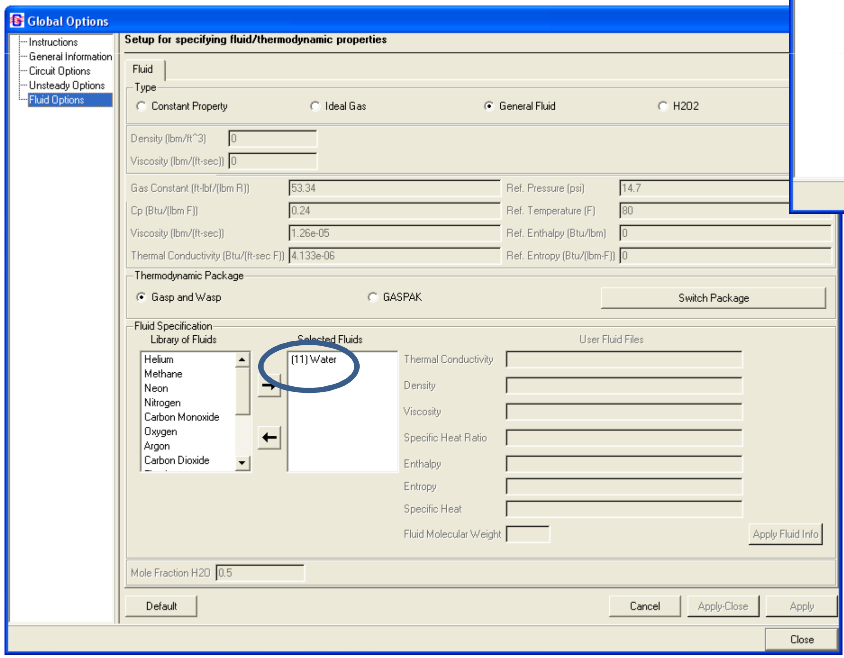
Second Law Option

Program Options (cont.)

Activate INERTIA option globally

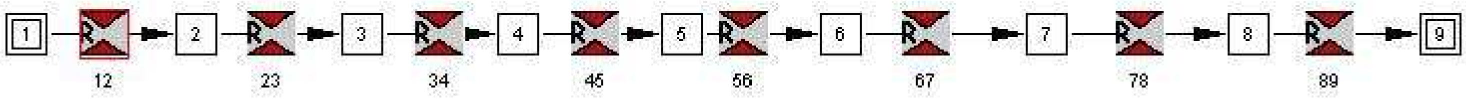
- This only means that the inertia term becomes <u>selectable</u> in the branches



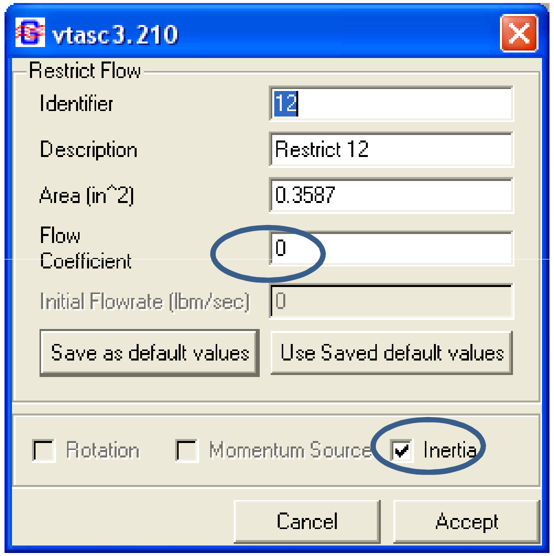


Fluid is steam (water)

Branch Geometry

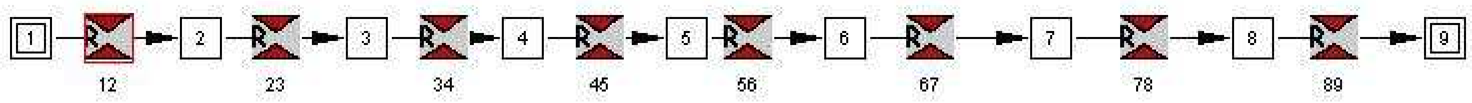


Branch	Area (in^2)
12	0.3587
23	0.2243
34	0.1901
45	0.2255
56	0.3948
67	0.7633
78	1.2520
89	1.6286



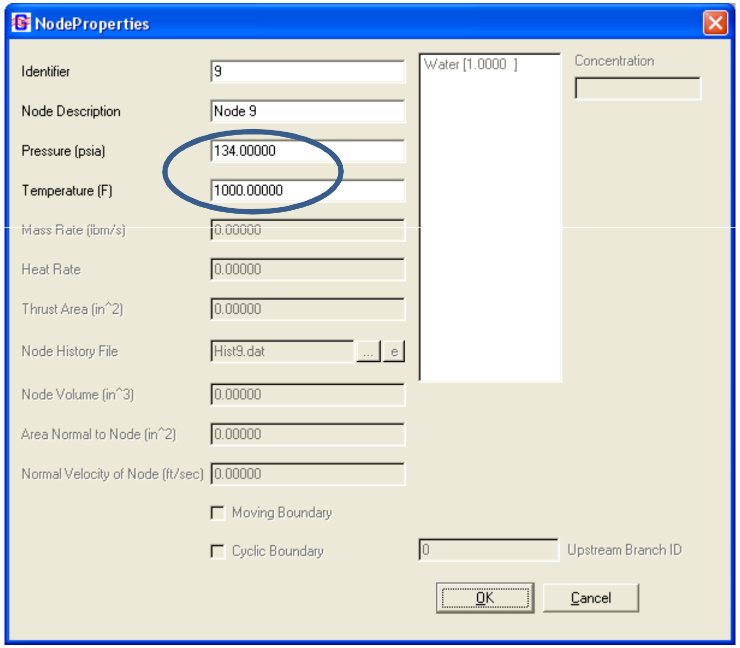
- Set restriction flow coefficient to 0.0 (isentropic)
- Activate inertia term in each branch

Boundary Conditions



- Run five cases
- Adjust downstream pressure for each case

Run	P1 (psia)	T1 (F)	P9 (psia)	T9 (F)
1	150	1000	134	1000
2	150	1000	100	1000
3	150	1000	60	1000
4	150	1000	50	1000
5	150	1000	45	1000



Results of Parametric Computations

Determine the choked flowrate through the nozzle

Run	P9 (psia)	F (lb_m/s)
1	134	
2	100	
3	60	
4	50	
5	45	

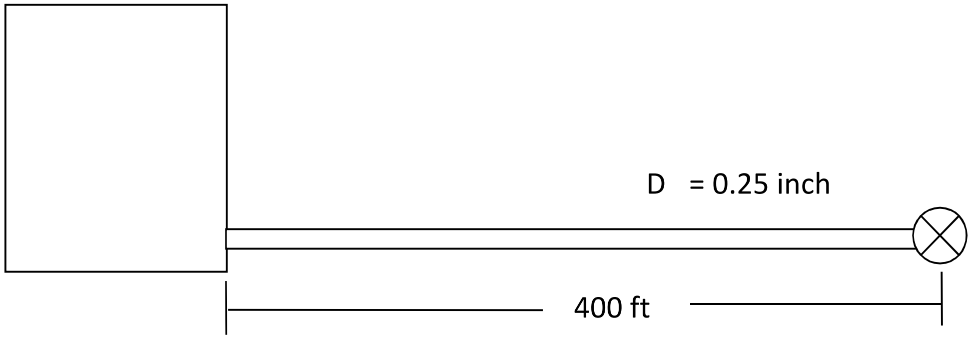
- How does the choked flowrate compare to the hand-calculated value of 0.327 lb_m/s?
- How does the throat temperature (T4) compare to the hand-calculated value of 799 °F?

Study of the Results

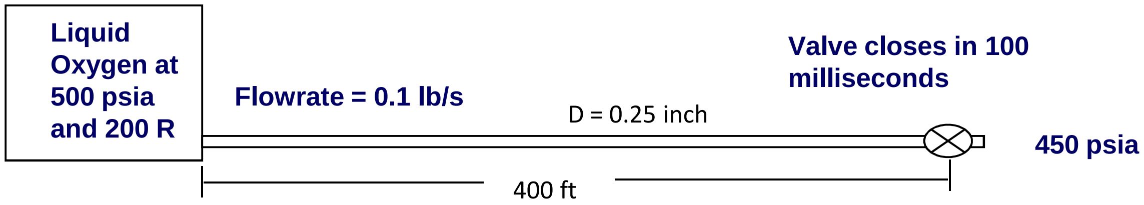
- Study *tut1.out* to note the following facts:
  - Pressure is decreasing from inlet to throat and increases from throat to exit in subsonic flow (Exit Pressure = 135 psia)
  - Temperature follows a similar trend; temperature changes due to expansion and compression
  - Entropy remains constant due to isentropic assumption
  - With lower exit pressure, flow becomes supersonic in the diverging part and becomes subsonic with the formation of shock wave
  - Flowrate remains constant with exit pressure once choked flow rate is reached

Tutorial – 2

SIMULATION OF FLUID TRANSIENT FOLLOWING SUDDEN VALVE CLOSURE



FLUID TRANSIENT SCHEMATIC

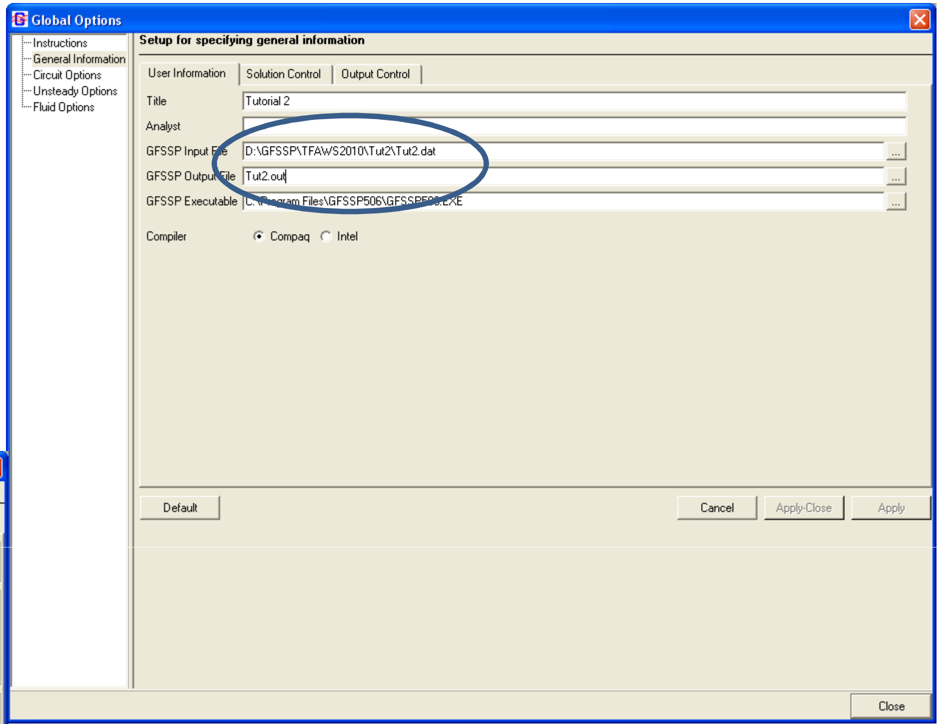


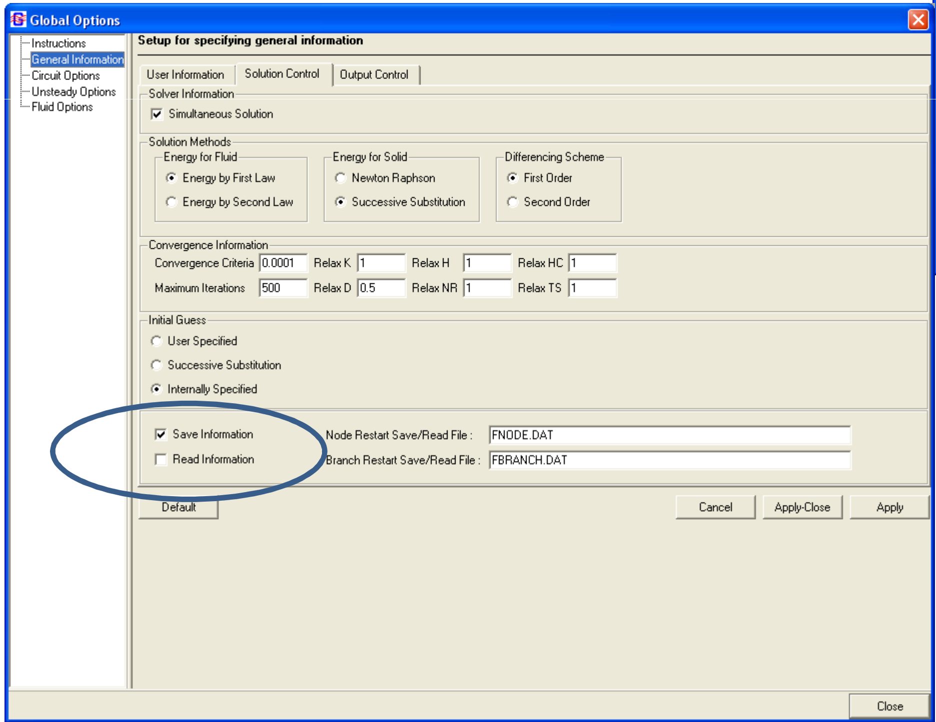
Problem Considered:

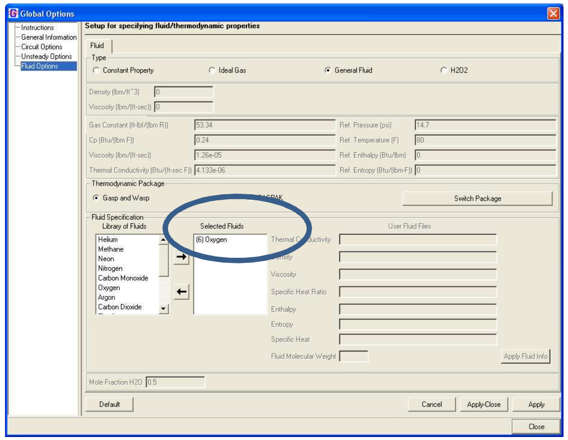
•Time dependent Pressure and Flow rate history during and after valve closure

Part 1: Build Steady State Model

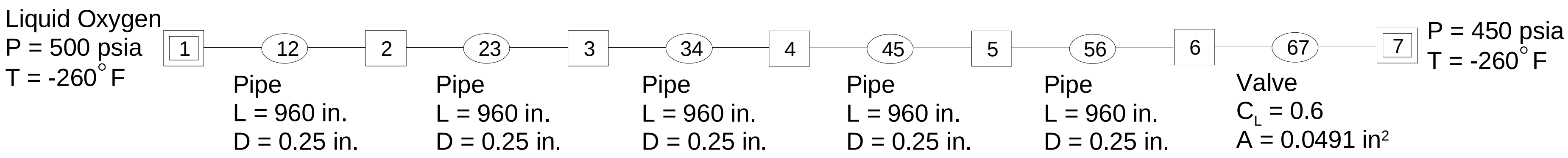
- Input File: Tut2.dat
- Output File: Tut2.out
- Check Save Information to save the steady-state solution in the restart files
- Fluid is LOx

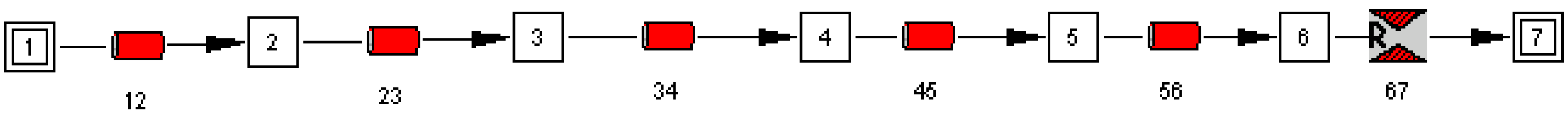




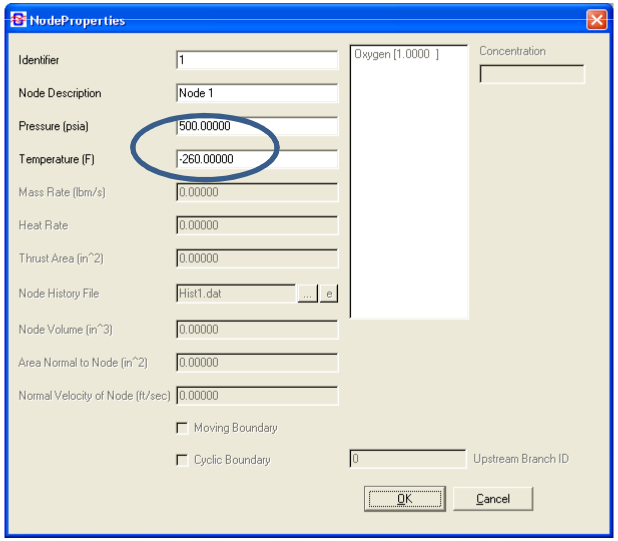


Part 1: Build <u>Steady State</u> Model (cont.)



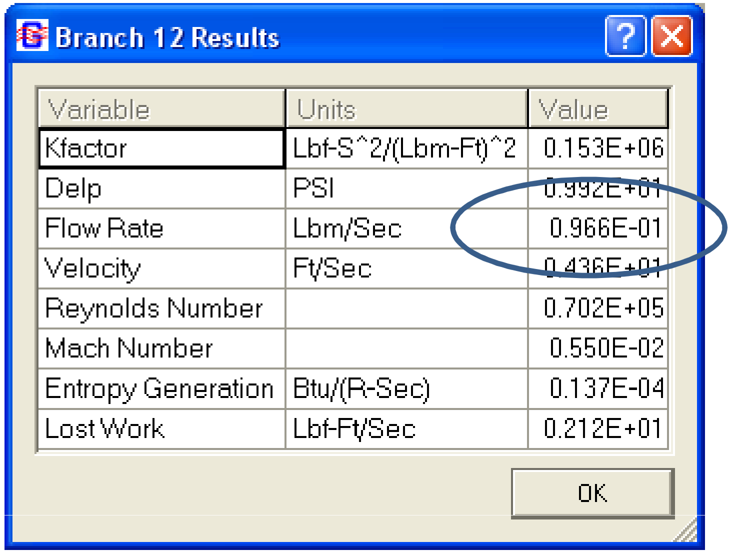


- Build the model on the canvas
- Set boundary conditions
- Set pipe and restriction parameters
  - Assume smooth pipe (ε=0)



Part 1: Build Steady State Model (cont.)

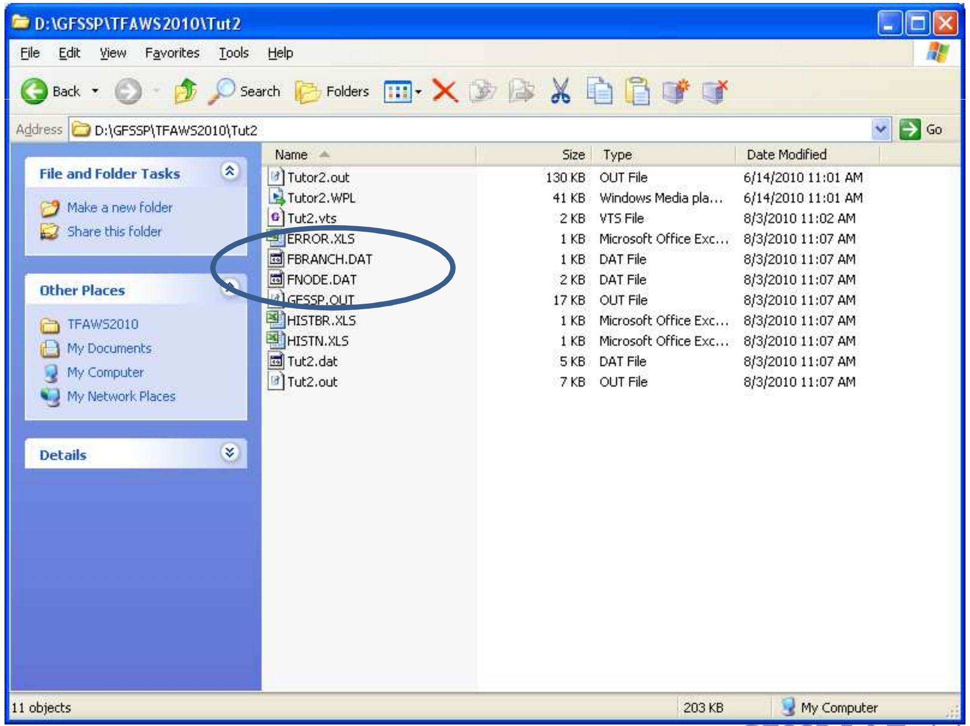
- Run the steady state model
- Check that the flowrate is ≈0.1 lb_m/s
- Note that the results have been saved in the restart file



Branch 12 Results

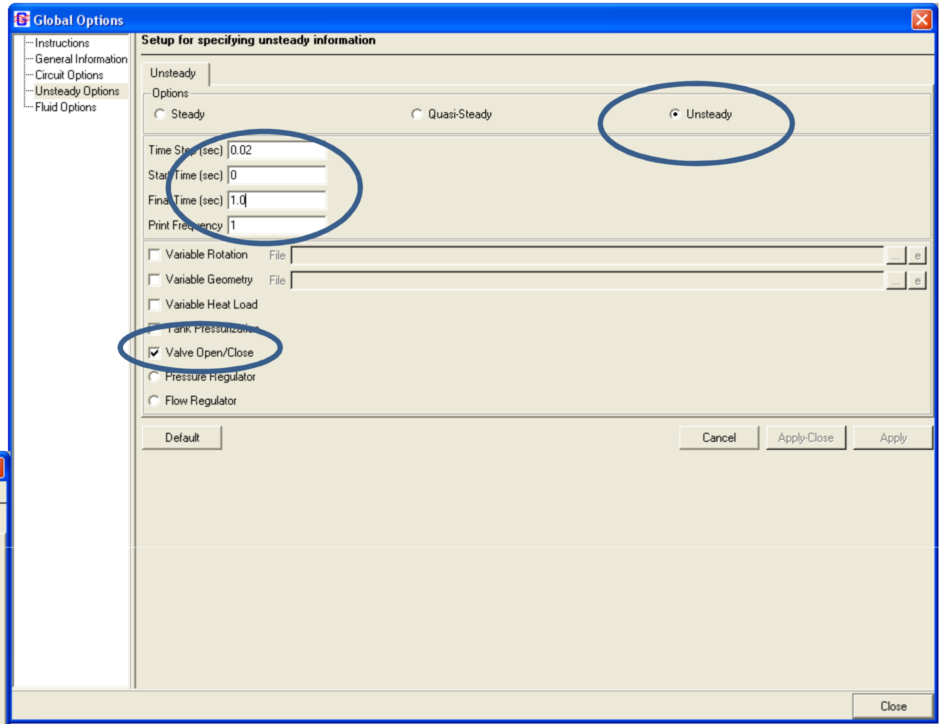
Variable	Units	Value
Kfactor	Lbf-S^2/(Lbm-Ft)^2	0.153E+06
Delp	PSI	0.992E+01
Flow Rate	Lbm/Sec	0.966E-01
Velocity	Ft/Sec	0.436E+01
Reynolds Number		0.702E+05
Mach Number		0.550E-02
Entropy Generation	Btu/(R-Sec)	0.137E-04
Lost Work	Lbf-Ft/Sec	0.212E+01

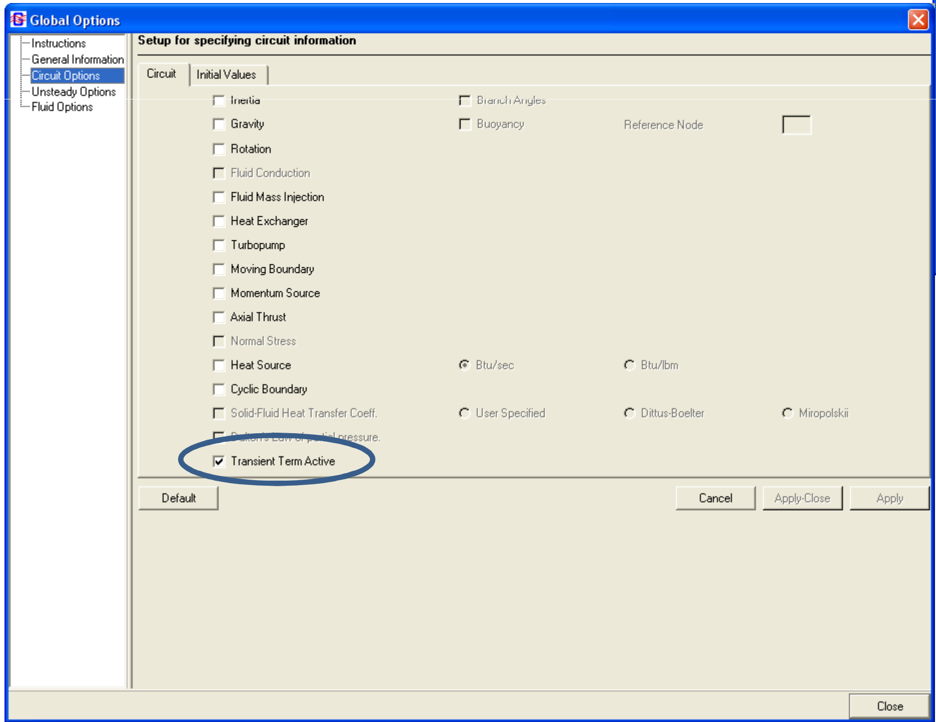
OK



Part 2: Build Transient Model

- Convert the model to transient
    - Time step = 0.02 s
    - Run time = 1.0 s
    - Check Valve Open/Close Unsteady Option

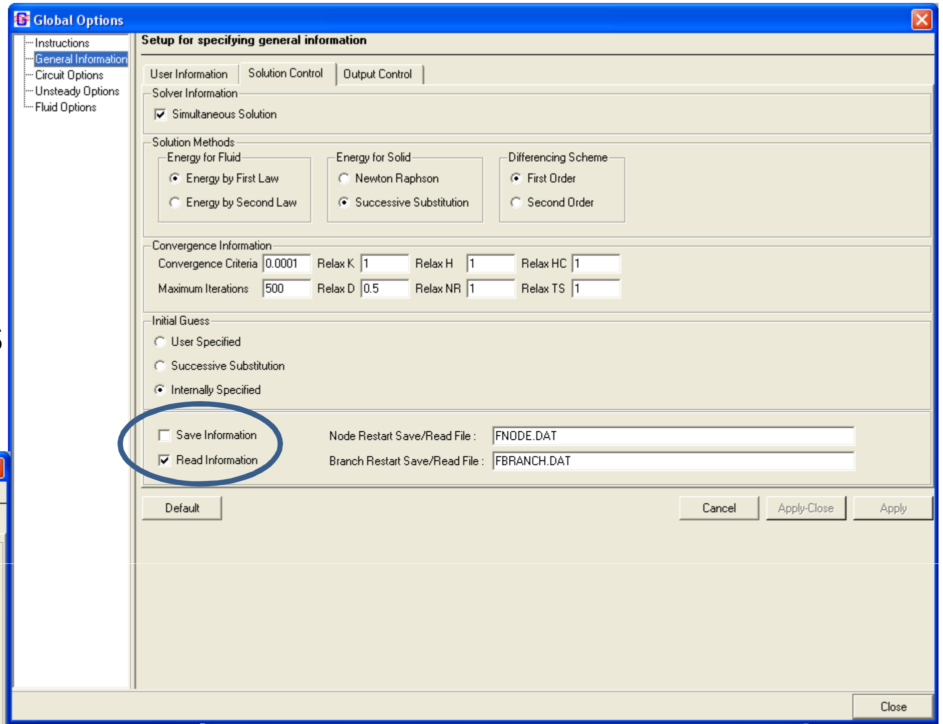


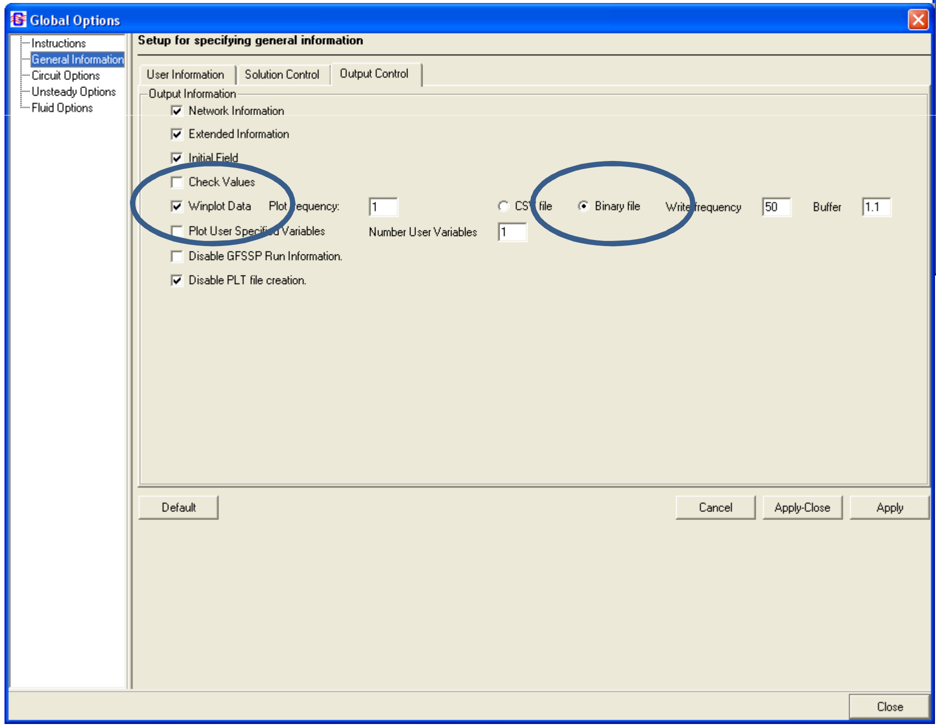


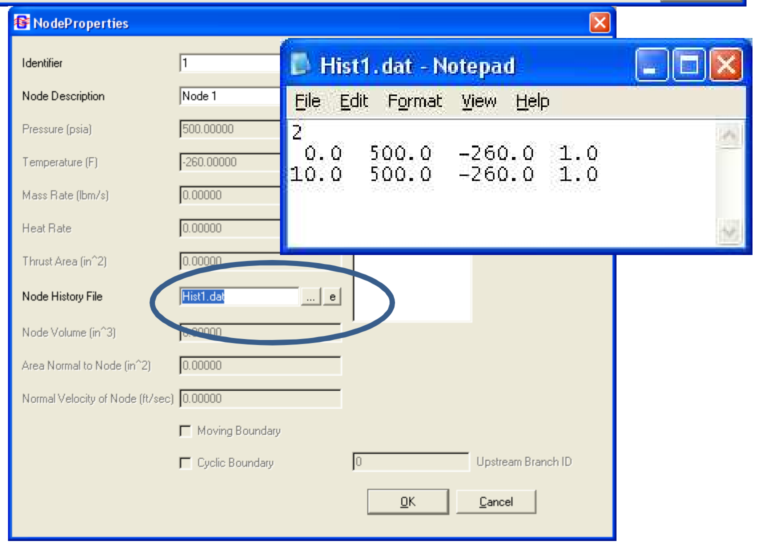
- Check Transient Momentum Term Option

Part 2: Build Transient Model (cont.)

- Uncheck SAVE restart file box
- Check READ restart file box
- Check Winplot binary output
- Create history files for boundary nodes







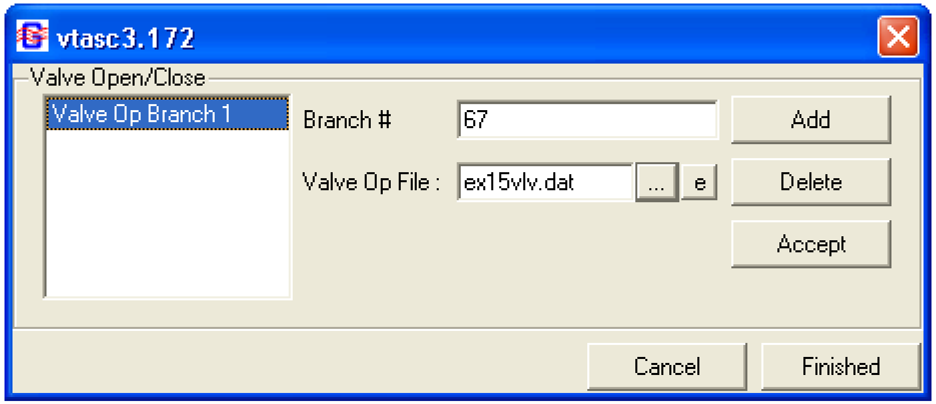
Part 2: Build Transient Model (cont.)

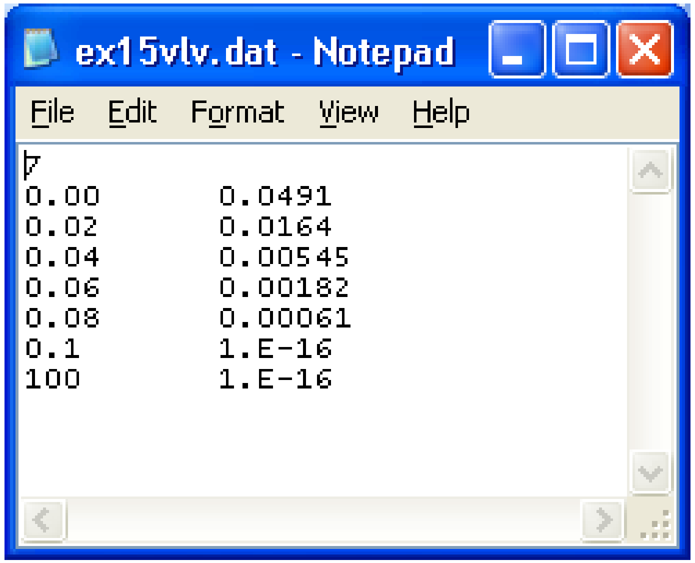
•Open the Valve Open/Close dialog box from the Advanced menu

•To represent the valve closing, the area of Branch 67 will vary as a function of time

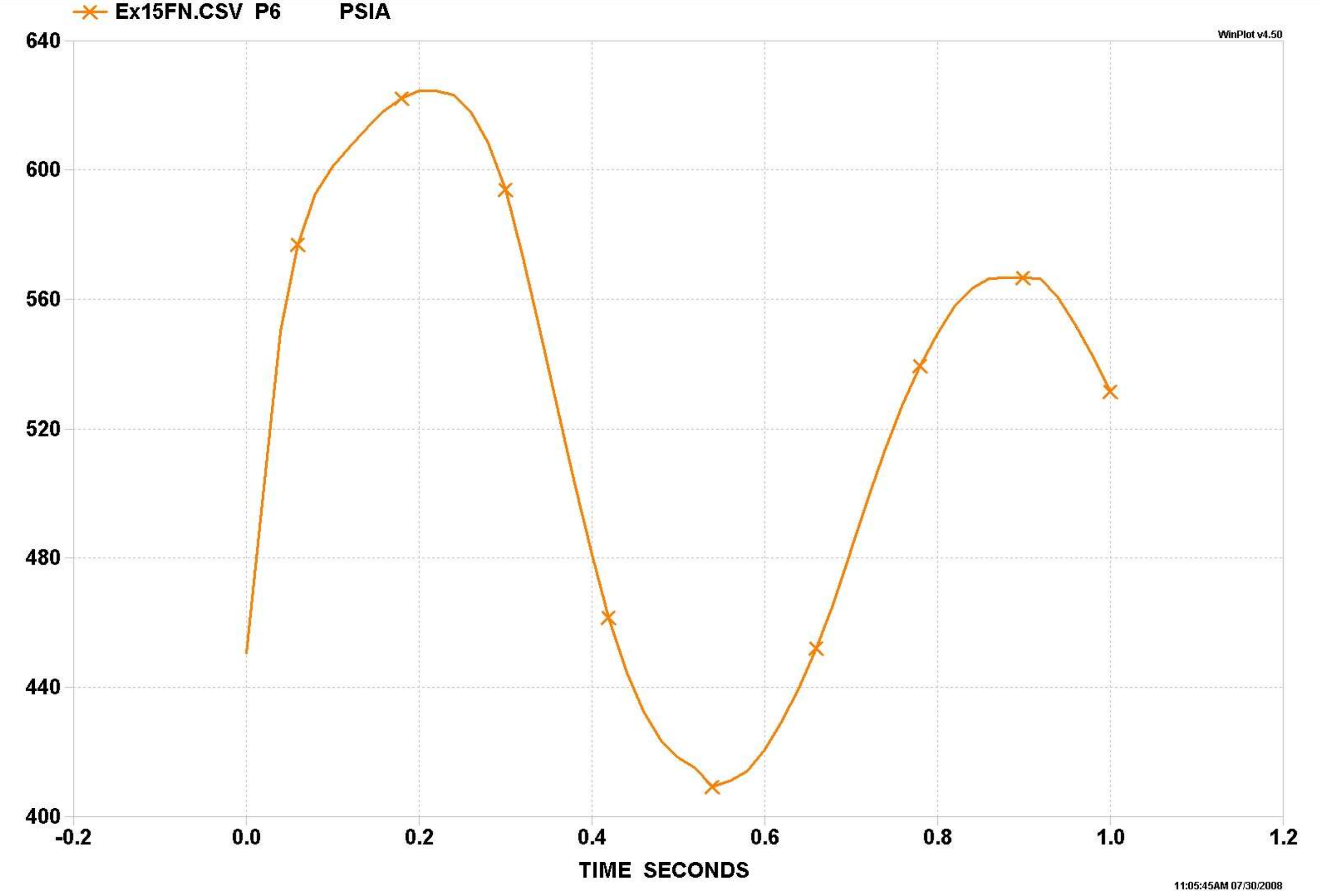
Valve Closure History

Time (Sec)	Area (in^2)
0.00	0.0491
0.02	0.0164
0.04	0.0055
0.06	0.0018
0.08	0.0006
0.10	0.00





Pressure History at Valve



STUDY OF THE RESULTS

- Plot pressure and flowrate history
  - Peak pressure approximately 620 psia
- Estimate the predicted period of oscillation and compare with the following formula
  - Period of Oscillation = 4L/a
  - Where L = length of the pipe
  - And a = Speed of sound = 2462 ft/sec for LOX
- Plot compressibility history and note variation of compressibility with time